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GENESIS OF THE ALKALINE ROCKS

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INTRODUCTION

The eruptive sequence in the compact and quite isolated igneous complex at Ascutney Mountain, Vermont, opens with gabbro and closes with dike rocks, including its chemical equivalent, diabase. The gabbro seems locally to merge into a type intermediate between essexite and a basic diorite. That body is cut by dikes of a mafic rock which shares the characteristics of monzonite and ideal essexite.[1] Intruding the gabbro, "diorite," and essexitic monzonite are several stocks or thick dikes of alkali-rich syenites, themselves cut by a stock of alkaline granite. Still younger are the diabase dikes.

The study of Ascutney Mountain, begun in 1893, introduced the writer to the problem of the so-called alkaline rocks. There he first became skeptical of the dogma that the alkali-rich magmas have originated independently of the subalkaline (lime-alkali)

[1] The relation between this microperthite-orthoclase-plagioclase rock and the gabbro-"diorite" body, described in *Bull. 209, U.S. Geol. Surv.*, 1903, was proved in 1916.

magmas. That doubt was confirmed during observations in the volcanic fields of France, Italy, and Germany, in the colossal igneous fields of the North American Cordillera, and in Hawaii.

North of the Hawaiian volcano, Hualalai, soda-rich trachyte rests on, and is surrounded by, great flows of olivine basalt. This spectacular association could not fail to recall the problem which had been so baffling during the interval of sixteen years. More than ever the writer was convinced of the extreme intimacy of the alkaline and subalkaline suites of igneous rocks. The relatively small volume of all known alkaline rock and the small absolute sizes of alkaline bodies had suggested their derivation from the overwhelming subalkaline magmas, but it was not until the Hawaiian lavas were closely considered that a promising clue to an explanation was found.

The hypothesis involving that clue was published in 1910. One outstanding fact on which the hypothesis is based is the common occurrence of feldspathoids in the alkaline rocks instead of, or alongside, feldspars, which are the dominant constituents of the subalkaline rocks. The presence of nephelite or leucite signifies a lack of silica available for full saturation of soda or potash or both, suggesting some desilication of original subalkaline magma. Secondly, the concentration of alkalies in many alkaline rocks means that some agent or group of agents had collected the alkalies from the original magma. No success characterized the attempt to imagine adequate causes for the desilication or for the enrichment in alkalies, if the magma remained throughout purely juvenile in origin. The writer was thus led to assume the absorption of foreign material as the responsible condition. Such material is basic sedimentary rock. The most basic, large-scale, and widely spread rocks are limestone and dolomite. Also on account of the relative chemical simplicity of the carbonates the writer laid stress on these particular sediments. Unfortunately certain authors have thought that it was intended to explain all alkaline rocks by the interaction of resurgent carbonates with subalkaline magma, though that was disclaimed in the original paper.[1] In 1913 the hypothesis was elaborated and the very important case of the

[1] *Bull. Geol. Soc. Am.*, XXI (1910), 108, 113, 114, 116.

syenites was speculatively treated. For those rocks, the most voluminous of the whole alkaline suite, *hydrous*, *basic* sediments (with or without calcareous associates) were considered as the probable agents of desilication and concentration of alkalies.[1] Thus, while the absorption of small amounts of limestone or dolomite seems to be the chief cause for the differentiation of most nephelitic and leucitic rocks, many other alkaline types were explained by the assimilation of hydrous sediments, in indefinitely varied mixture with one another or with more siliceous rocks or with carbonate rocks.

During the last four years new field observations and some experimental work bearing on the subject have been reported, and important papers on general theory as well as on special points have been published. A review of these matters and correlated observations of older date is the purpose of the present article. A full discussion of the origin of alkaline rocks is not attempted, but rather a supplement to corresponding chapters in the writer's *Igneous Rocks and Their Origin*. After brief discussion of the field and chemical studies, Bowen's petrogenic theory, the strength of which is so largely measured by its ability to explain the alkaline rocks, will be analyzed in some detail.

RECENT FIELD OBSERVATIONS

Many investigators of alkaline rocks still continue to give merely petrographical descriptions. Others discuss the origin of the rocks, but are content to refer the various types to differentiation without giving any adequate idea of what was differentiated. A few writers during the last four years have more seriously considered the questions of origin, and it is worth while to note their findings.

Relation of the alkaline and subalkaline suites.—From new localities have come proofs of the exceedingly close time and space associations of the alkaline ("Atlantic") and subalkaline ("Pacific") eruptives. Among those who have lately laid emphasis on the point are Lacroix, Smyth, Cross, Washington, Holmes, Bowen, Harker, and the writer.[2]

[1] R. A. Daly, *Igneous Rocks and Their Origin* (New York, 1914), p. 395.

[2] A. Lacroix, *Bull. soc. géol. France*, X (1910), 91; *Comptes rendus*, CLV (1913), 538; C. H. Smyth, *Amer. Jour. Sci.*, XXXVI (1913), 41; W. Cross, *Prof. Paper 88, U.S. Geol. Surv.*, 1915, pp. 85, 91; H. S. Washington, *Compte rendu, Cong. géol. internat.*

The cited paper by Washington is worthy of special mention. He is certainly right in pointing out the vague nature of the expression "alkaline suite." The recognized difficulty of assigning some rocks to it rather than to the subalkaline suite matches the perfect transition between the two series. The use of these names involves danger to correct thinking if, while using them, the petrologist does not resist the idea that the two distinct suites really existed as such from the earth's beginning. Nevertheless some general name for alkali-rich rocks and their syngenetic associates is useful, and "alkaline" will be here so employed.

An illustration of the bond between the two suites is seen in the relation of albite-rich or oligoclase-rich lavas, the so-called spilites, to normal basalt, dolerite, or diabase.[1] Sargent has just proposed the term "auto-metamorphism," symbolizing his conclusion that the Lower Carboniferous spilites of Derbyshire have been derived from common basaltic magma through the "retention of volatile constituents resulting from the physical environment of a submarine flow."[2]

Though a follower of Becke in his interpretation of the "Atlantic" and "Pacific" suites, Winkler sees the intimacy of the two in the Eastern Alps (Steiermark). There the Pliocene was a time of extrusion of "Atlantic" magma, from which nephelite regularly crystallized. Winkler explains contemporaneous rock types more characteristic of the "Pacific" suite (normal basalts) by silication due to the solution of quartzose sediments in the original "Atlantic" magma.[3]

Ice River intrusion, British Columbia.—Allan states that the Ice River intrusive furnishes "a very strong case in favour" of the sediment-syntectic hypothesis (desilication) as applied to nephelite syenites and their allies—an explanation squarely opposed to that

(Ottawa, 1914), p. 235; A. Holmes, *Mineral. Mag.*, XVIII (1916), 71; N. L. Bowen, *Jour. Geol., Suppl.*, XXIII (1915), 59; *ibid.*, XXV, 220; A. Harker, *Jour. Geol.*, XXIV (1916), 556; R. A. Daly, *Bull. Geol. Soc. Am.*, XXVII (1916), 329.

[1] Cf. S. von Szentpétery, *Mitt. Mineral. Geol. Sammlung des Siebenbürg. Nationalmuseums*, Kolozsvar, Band I, No. 2, 1912.

[2] H. C. Sargent, *Nature*, XCIX (1917), 59; *Phil. Mag.*, XXXIII (1917), 535.

[3] A. Winkler, *Zeit. für Vulkanologie*, I (1914), 182.

given by Winkler for the Alpine rocks just mentioned. In order to reach its present position the magmatic material at Ice River "had to travel through at least 10,000 feet of limestone or highly calcareous sediments of Cambrian age, and 3,000 feet of more or less calcareous shales."[1] Allan also finds evidence of resurgent carbon dioxide, volatilization of the alkalies, and gravitative adjustment in this remarkable complex. Large xenoliths of shale and limestone show plainly (p. 190) the introduction of alkaline solutions, which have caused in the xenoliths the crystallization of feldspars, nephelite, sodalite, and cancrinite, along with many lime minerals.[2]

Haliburton County, Ontario.—Foye has made a very important contribution to the subject as a result of his study of the nephelite syenites and adjacent formations in Haliburton County, Ontario.[3] Adams and Barlow had proved a large part of the associated amphibolites and pyroxenites to be due to the contact metamorphism of thick limestones by numerous granitic sills and "batholiths" (these described by Foye as laccoliths).[4] Foye was able to show that the magmatic emanations so largely responsible for this profound metamorphism were very like the material that went to form the nephelite syenite of the region. The total volume of the amphibolites thus formed is many times greater than the total volume of the nephelite syenite, making all the more probable the view that this alkaline rock has been formed pneumatolytically. Foye goes farther and concludes that the gases engaged in segregating the alkalies included resurgent carbon dioxide (and water), derived from the limestones and other interbedded sediments as these reacted with the granitic magma. Granite injections and limestones together made a "gigantic steam pack," from which alkaline volatile matter was expelled. Part of this formed a large proportion of the amphibolite; a much smaller part was trapped

[1] J. A. Allan, *Memoir 55, Geol. Surv. Can.*, 1914, p. 211.

[2] Compare the nephelitic schliers and nephelite-lined vugs in the nephelite basalt of the "Löbauer Berg," described by J. Stock, *Tschermaks Min. und Petr. Mitt.*, IX (1888), 438.

[3] W. G. Foye, *Amer. Jour. Sci.*, XL (1915), 413.

[4] W. G. Foye, *Jour. Geol.*, XXIV (1916), 783.

in the sill and laccolith chambers and finally crystallized as nephelite syenite and its by-products.

The crescentic laccolith near Tory Hill illustrates gravitative differentiation, also well displayed in several other of the thicker alkaline bodies. The maximum thickness of the laccolith is only about three hundred feet, yet it shows a striking variation from top to bottom as here indicated:

a) Pegmatitic nephelite syenite, with specific gravity of 2.674; carries microperthite (59 per cent), nephelite (21 per cent), and albite (12 per cent); contacts with limestone roof.

b) Monmouthite, with specific gravity of 2.719; carries nephelite (57 per cent), albite (9 per cent), scapolite (10 per cent), and biotite (22 per cent).

c) Hornblende-nephelite rock, with specific gravity of 3.124; carries nephelite (30 per cent), albite (7 per cent), pyroxene (20 per cent), hornblende (30 per cent), garnet (7 per cent), and primary calcite (5 per cent).

d) Garnet-pyroxene rock, with specific gravity of 3.383; carries albite (3 per cent), pyroxene (34 per cent), garnet (37 per cent), and primary calcite (25 per cent); contacts with limestone floor.

The mineralogical composition of the Tory Hill and other laccoliths of the district directly indicates the probability of syntexis between magma and limestone. Of course there is no necessity of assuming that all, or even the larger part, of this assimilation took place at the visible contacts.

Palingenesis in relation to the problem.—Basaltic magma may not at all have participated in these Ontario developments. The writer suspects that, like many other pre-Cambrian invasions of magma, the petrogenic cycle was not opened by the abyssal injection of basalt. Along with Lawson, Sederholm, and other workers in pre-Cambrian complexes, one is rather tempted to regard the activity of the granite magma as due to palingenesis, that is, refusion of the crustal granite at a level not far below that to which erosion has brought the general surface of Haliburton County. This whole field exemplifies the difficulty of applying to the granites of the older pre-Cambrian terranes any petrogenic scheme that

may succeed in explaining post-Cambrian eruptive bodies and sequences.

Azof region, Russia.—Guinsberg believes that the limestone-syntectic hypothesis is valid for the nephelitic and other alkaline rocks studied by him in the Azof (Mariupol) region, even though they do not make visible contact with limestones at all. He

> explains the origin of the nephelite-syenite by the mixture of a basalt-magma with limestone followed by a differentiation in alkali rocks and pyroxenite. Although the limestones were not discovered in this district, the presence of sedimentary rocks such as quartzite was established. In the neighboring district of Berdjansk, which forms the continuation of the same crystalline area, Morozewicz found among the crystalline schists together with quartzites also limestone and graphitic gneiss.[1]

Reinhardswald, Germany.—Apel's recent work on the Reinhardswald district of Northern Germany gives the petrography of a large number of volcanic necks.[2] The eruptives include: common basalt, dolerite, enstatite dolerite, trachydolerite, nephelite basalt, melilite-bearing nephelite basalt, leucite basalt, leucite basanite, limburgite, and nosean-bearing limburgite. Other types represent the transition between nephelite basalt and leucite basalt.

This assemblage claims notice as another example of the close connection between alkaline varieties and feldspar basalt. Lepsius' geological map of Germany seems to show that the alkaline-lava vents are here largely or wholly confined to areas underlain by the Muschelkalk at the time when the volcanoes were active, numerous vents filled with feldspar basalt and dolerite appearing specially in Bunter Sandstein areas. The writer has not been able to check this generalization by reference to a large-scale geological map of the region, but has thought the question involved might well be put on record. In any case the possible chemical influence of the Muschelkalk on the magmas which fluxed, stoped, or exploded their way to the earth's surface needs investigation. The problem is complicated on account of the partial removal of the limestone by erosion since the volcanic epoch.

[1] A. Guinsberg, "Pierre le Grand à Pétrograde," *Annales de l'Inst. Polytech.*, XXV (1916), 435.

[2] K. Apel, *Neu. Jahr. für Mineralogie*, etc., B.B. XXXVIII (1914), 525.

Almunge, Sweden.—Among the most noteworthy publications of late years is Quensel's paper on the alkaline rocks of Almunge.[1] Consisting of dominant umptekite with an aplitic marginal zone and with huge inclusions of canadite (albite-nephelite syenite), these rocks form a stocklike body measuring 4.5 by 3.5 km. It cuts granite of two types. Quensel's memoir is full of valuable information, but two chief points are of present importance. One is the abundance of the two lime minerals, vesuvianite and primary cancrinite, in the canadite. The other is Quensel's suggestion as to the genesis of this rock. His statement may be quoted (p. 196):

> Vesuvianite has always been considered a typical mineral of the contact metamorphism of calcareous rocks. It seems difficult to explain its presence in the Almunge canadites in any other way than that it represents the remains of otherwise fully assimilated calcareous sediments. Its occurrence would then be comparable with the primary calcite of Alnö or Bancroft, formed through assimilation of limestones by the igneous magma under such circumstances that the CO_2 could not abscond. The very essential amount of cancrinite in all these rocks would then probably be a manifestation of the same geological features. The presence of a hydrated mineral in an igneous rock is hardly more remarkable than CO_2 partaking in the constitution of other magmatic minerals under similar circumstances.
>
> Though nothing can be said with certainty about the origin of the alkaline rocks, several features seem, however, to point to the possibility of the origin of nepheline-syenites in some way having been connected with the assimilation of calcareous sediments. As previously mentioned, paragneisses with interbedded limestone are found at no very great distance south of the area and may possibly be present at deeper levels within the Almunge district itself.

The writer is free to admit that future field work at a number of other localities is not likely to yield results positively favorable to the sediment-syntectic hypothesis for the alkaline rocks. Yet the

[1] P. D. Quensel, *Bull. Geol. Inst. Upsala*, XXII (1914), 129. While the proofs of the present paper were being read, Thorolf Vogt's account of the rocks of Hortavaer, Norway, reached America [Videnskapsselskapets Skrifter, I Mat.-naturv. Klasse, Christiania (1915), No. 8]. Vogt describes the peripheral solution of large limestone masses in intrusive subalkaline magma, with the resulting generation of alkaline pyroxenes which chiefly compose "hortite," a new plutonic type. He concludes that the injection temperatures were in the neighborhood of 1300° C. for the intrusives at Hortavaer and at Alnö, Sweden! Still other features of Vogt's paper are significant in connection with the sediment-syntectic hypothesis, which he regards as sound at least in part, but space fails for a fuller discussion of this careful petrological study.

apparent or real absence of basic sediments at those places is not immediately compelling to anyone who remembers the complex conditions due to deep erosion, to inadequate exposures, to "staccato" injection,[1] to the lateral migration of magmas, as proved in the case of sill or laccolith, and to the probable fact that most pre-Cambrian granite (and orthogneiss) has been concordantly injected and may therefore in a given instance cover thick, basic sediments not locally exposed. The last-mentioned principle affects the negative evidence for appropriate country rocks around the alkaline eruptives of the Julianehaab district, the Kola Peninsula, Cripple Creek, certain localities in New Hampshire and East Africa, etc.

The repeated objection that some granites, granodiorites, and other subalkaline bodies cut limestones and yet do not show obvious chemical reaction with the sediments is not necessarily valid. Such contacts may simply indicate the respective magmatic temperatures to have been too low for the reaction. Before stoping or other mechanical movements had established any of these contacts the temperature may have been higher, so that solution of limestone was then possible. However, unless the limestone made a considerable part of the whole rock mass dissolved (otherwise likely to be composed of siliceous country rock), the effects of the solution of limestone might be masked by the differentiation of each great body of magma. In a special case a batholith may have stoped its way to the limestone just as the dissolving power of the magma was approaching zero.

Hawaii.—Cross's valuable memoir on the Hawaiian lavas bears the conclusion that the alkali-rich rocks and melilitic rocks of the archipelago are "products of the same general process of differentiation [of original basalt] as the other rocks with which they are associated."[2] He rejects the sediment-syntectic hypothesis, partly because he doubts that limestones are "associated with the older lavas of the archipelago." He fails also to see how "superficial deposits of coral limestone . . . . can gain access to the volcanic conduit in mass sufficient to produce any notable result." Yet

[1] Cf. R. A. Daly, *Amer. Jour. Sci.*, XLIII (1917), 444.

[2] W. Cross, *op. cit.*, p. 90.

thick limestones do underlie the lavas of Oahu, and it is scarcely credible that during the slow growth of the volcanic piles through 2,500 fathoms of warm Pacific water there should be no interbedding of calcareous oozes, coarser shell deposits, or coralliferous limestones. The magma of a volcanic vent, locally fluxed through such a composite, could not fail to incorporate some calcareous material. The remaining question is as to how much assimilation is "sufficient to produce any notable result." The answer is—comparatively little. Since alkali-rich rocks are very rare in Hawaii and, so far as known, of small individual volumes, the absolute amount of limestone assimilation need be very slight and in any case quite local.

The syntexis of basalt and limestone is positively suggested by the several occurrences of nephelite-melilite basalt in and around Honolulu, where deep borings have proved the existence of thick limestones which must have been traversed by the conduits of these lavas. In the same region are nephelite basalts. As Cross states, it may be "certainly true that the alkali-rich lavas are not present about Honolulu," but the first step in limestone syntexis is obviously not an alkali-rich magma. That can originate only under conditions allowing drastic differentiation. According to the present writer's view, the flows of melilitic and nephelitic basalts are quenched phases, erupted before much concentration of alkalies in the vent was possible. As Bowen agrees, melilite is possibly a direct sign of syntexis with limestone rather than of pronounced differentiation. Ten years ago Becker published the hypothesis that the melilite in the basalts of the Wartenberg and of Southwest Germany in general have resulted from the absorption of calcareous sediments.[1]

Tahiti.—Marshall, by actual field work, has well supplemented Lacroix's petrographic studies in Tahiti.[2] In the central pipe of the island he found an alkali-rich syenite associated with wehrlite and gabbro. This stocklike or necklike body traverses the flows

[1] Cf. N. L. Bowen, *op. cit.*, Suppl., XXIII (1915), 89; R. A. Daly, *Igneous Rocks and Their Origin* (New York, 1914), p. 436; E. Becker, *Zeit. deut. geol. Gesell.*, Band LIX (1907), 273.

[2] P. Marshall, *Trans. New Zealand Inst.*, XLVII (1915), 361.

of dominant, common basalt. The syenite and other alkaline types have suggested the problem of origins to Marshall. He finds no evidence favoring the sediment-syntectic hypothesis in this case. A chief ground for doubting it is the assumed lack of limestone in the volcanic pile. Marshall admits that globigerina ooze veneers the submarine flanks of Tahiti, but implies that neither ooze, coralliferous limestone, algal limestone, nor shell limestone was interbedded with the basaltic flows during the slow submarine growth of the volcano. Again one must ask if such interbedding can, under the tropical conditions, possibly be doubted. Again, too, the required amount of assimilation of limestone and other sediments would be small.

Queensland.—Richards has published an excellent study of the Tertiary volcanic rocks of southeastern Queensland.[1] These are divisible into three stratigraphic divisions. The lowest is composed of common basalts. The middle division includes augite andesite, rhyolite, comendite, trachyte, soda-trachyte, phonolitic aegirite trachyte, and pantellerite. The upper division is dominantly basaltic, with flows of olivine basalt, olivine-free basalt, andesitic basalt, oligoclase basalt, and andesite. The alkaline rocks "constitute at the most 5 per cent of the volcanic material." Richards regards all types as mere differentiates of a single original magma and follows the all too common plan of calculating its composition from the volumes and compositions of the visible rocks only. Inasmuch as no reckoning is made of the other magmatic phases that must have remained in the magma chambers below the earth's surface, the estimate is entirely misleading and, for its purpose, of no immediate value.[2]

On account of the relatively small amount of limestone in the country rocks, Richards finds unsatisfactory the sediment-syntectic hypothesis in explanation of the Queensland alkalines. However, limestone is not necessarily a partner in a syntectic from which trachytes, pantellerites, or comendites are differentiates. The writer has indicated the grounds for regarding shales and other subsiliceous, hydrous sediments as more influential in the generation

[1] H. C. Richards, *Proc. Roy. Soc. Queensland*, XXVII (1916), 105.

[2] The same principle applies to alkaline provinces in general.

of trachytic and syenitic magmas generally.[1] The solution of small amounts of Mesozoic and Paleozoic non-calcareous sediments (or of their connate waters) in basaltic magma may be primarily responsible for the quite subordinate, alkali-rich lavas of Queensland. The traces of calcareous material in these sediments might co-operate in the underground reactions, but carbonates were not in chief control.[2]

SPECIAL CHEMICAL CONSIDERATIONS

"Saturation" in igneous rocks.—Shand expresses a suggestive idea in distinguishing "saturated," "undersaturated," and "oversaturated" igneous rocks.[3] Saturated rocks are those that contain only minerals which are capable of forming in the presence of free silica. Any rock containing free quartz or tridymite of magmatic origin is said to be oversaturated. Undersaturated rocks are composed, wholly or in part, of minerals unsaturated with silica. Shand's list of unsaturated minerals includes leucite, nephelite, sodalite, nosean, analcite, cancrinite, hauyne, melanite, melilite, magnesian olivine, corundum, and perovskite—all characteristic components in alkaline rocks.[4]

One of the causes for undersaturation Shand finds in assimilation. He writes (p. 511):

> When the invaded rock is a carbonate or other non-silicate rock, or contains much lime, magnesia, or iron in the form of oxide or carbonate, then the advantage as regards absorbing power lies with the saturated and oversaturated magmas, which can yield first their excess of silica, and secondly a further quantity of silica due to the reduction of sodium, potassium, calcium, and magnesium molecules from the saturated to the unsaturated state. In this way a saturated or oversaturated magma may become undersaturated.

[1] R. A. Daly, *Igneous Rocks and Their Origin* (New York, 1914), pp. 393, 410.

[2] The remark of Richards (p. 190), that "Dr. Jensen has also advocated the assimilation of carbonate rocks by the parent magma with the resultant production of alkaline material," is hardly a correct rendering of Jensen's hypothesis. Jensen assumes the precipitation of "alkaline salts" to the floor of the primitive ocean, their burial, and their later fusion and fluxing with the silicates of the overlying rocks. The present writer has not "elaborated this view," as Richards states.

[3] S. J. Shand, *Geol. Mag.*, X (1913), 508.

[4] See J. Morozewicz, *Tschermaks Min. und Petr. Mitt.*, XVIII (1898), 224. A. Holmes (*loc. cit.*, p. 71) points out that the basalts associated with the alkaline lavas of East Africa are also undersaturated with silica.

He favors the view that this condition applies to many alkaline rocks.

Among the consequences of undersaturation, according to Shand (p. 510), is the tendency of foyaitic or phonolitic magmas to enter "into chemical combination with the silica of invaded rock masses. The reactions thereby induced would be exothermic, and would tend to raise the temperature of the magma. . . . . The access of heat produced in this way would in turn enable the magma to perform a further amount of work in the way of mechanical solution." One is reminded of Ramsay's conclusion that the umptekite of the Kola Peninsula is probably due to syntexis between nephelite-syenite magma and siliceous sediments.[1] An analogy is found in Ussing's explanation of important masses of quartz syenite and soda granite in the Julianehaab district as products of reaction between augite-syenite magma and sandstone. Quensel, too, assumes syntexis between the umptekitic magma of Almunge and older granite, giving the observed transition between the corresponding formations.[2]

Shand notes the relative insignificance of alkaline rocks in volume; the dominance of oversaturated rocks among major intrusions; the dominance of saturated and undersaturated rocks (including basalts) among lavas and minor intrusions; and (p. 512) the

> strong suggestion that undersaturation may be characteristic of the deeper zones of the lithosphere, as oversaturation is of the higher. . . . . Those igneous rocks which have been brought up most rapidly from the earth's interior, and have solidified most rapidly in or on the crust, are to a marked extent undersaturated. Those which have slowly worked their way up into the crust (and have hence had abundant opportunity for absorbing silica) are found to be predominantly oversaturated.

Comparison may be made with the idea of granitic, continental maculae overlying a basaltic earth-shell.

[1] W. Ramsay, *Fennia*, XI, No. 2 (1894), pp. 74, 95. As above noted, Winkler has given proofs of the solution of quartz in basic Alpine lavas which he considers as belonging in the alkaline suite.

[2] N. V. Ussing, *Meddelelser om Grönland*, XXXVIII (1911), 59, 191, 197, 363, 366; P. D. Quensel, *op. cit.*, XII (1914), 196.

Action of "mineralizers" and of normal faulting.—Cross, Bowen, Foye, and others approve Smyth's reference[1] of the alkali-rich rocks to the work of gases or "mineralizers" operating in subalkaline magmas. The pneumatolytic origin of many nephelitic, sodalitic, and cancrinitic rocks has indeed long been clear to the French and other intelligent students of their mineralogy and texture. The next important questions are as to the origin of the gases and the cause of the concentration of the gases. Smyth regards the gases as (p. 45) "magmatic or 'juvenile' rather than resurgent" and joins Harker in thinking that their concentration along with the alkalies probably depends on crustal dislocation by radial movements in the earth.

He makes no other suggestion as to the reason why the mineralizers should, in general, not have the power to develop nephelite syenites and similarly undersaturated rocks in most plutonic complexes. Water and other mineralizers form tremendous emanations in andesitic volcanoes, yet many of these lack phonolitic, trachytic, or other alkali-rich lavas. The present writer has shown that many alkaline bodies occur in zones of intense tangential compression, while, on the other hand, subalkaline bodies are abundant in areas of radial dislocation. The statistics of distribution are far from supporting Harker's thesis. It suffers also from the improbability of another underlying assumption—that in every instance the parent subalkaline magma was nearly frozen at localities where normal faulting has caused the eruption of multitudes of small alkaline masses. The mechanism is seen to be one of almost infinite delicacy and hence of doubtful reality, at least on the scale demanded. One may observe also that normal faulting need not exert a notable squeezing-out effect if the magma chamber were not cut by the fault planes. A semiliquid mass inclosed in a downthrown or upthrown block would not necessarily undergo any differential stress. The alternation of liquid basalt and trachyte or phonolite at the same volcanic center is one of the more obvious difficulties with the speculation.

Further, the Harker hypothesis does not take proper account of the lamprophyres which usually close petrogenic cycles. While

[1] C. H. Smyth, *op. cit.*, p. 33.

aplites are explained, vogesites, spessartites, and odinites are not. If tinguaites or nephelite pegmatites represent residual liquids, what is the meaning of the camptonites or alnöites, so closely associated both in time and space with those alkaline types? In some nephelite-syenite areas camptonites not only are abundant but appear to be even younger than most of the tinguaites. There is manifest trouble in explaining *both* the salic and femic dike groups as crystallizations from residual liquid.[1]

Considering the weakness of the idea relating alkaline magmas to crustal dislocation of a special kind, Smyth's conception needs an important supplement. It would be strengthened if a more probable cause for the local, quite exceptional, concentration of the mineralizers and alkalies in purely juvenile magma were discovered. This has not yet been done. On the other hand, the local assimilation of sediments cannot, in general, fail to enrich subalkaline magmas in gaseous constituents, with the effect of segregating the alkalies, as the writer has long held.[2] In short, the combination of juvenile and resurgent "mineralizers" is believed to be a much

[1] A. Harker (*op. cit.*, p. 558) recently published a very doubtful argument in support of his contention that subalkaline ("calcic") rocks rather than alkaline rocks are genetically associated with "regions subjected to powerful lateral thrust." He writes: "If we examine those crystalline schists which are admittedly of igneous origin, together with foliated igneous gneisses, we find that they belong almost exclusively to the calcic branch. . . . . Alkaline crystalline schists as a whole are quite insignificant as compared with any single type in the calcic division. . . . . The striking disparity here noted is only one consideration among others which points to a peculiar distribution of alkaline and calcic igneous rocks in relation to crustal stresses."

Evidently the dynamic metamorphism in most of the cases cited followed *after* the respective eruptions. Some of the intervals between eruption and shearing have been proved to equal several geological periods. Can one assume that the resulting schistosity of the igneous bodies has any connection whatever with the generation of their magmas? Moreover, there is much to be said for the view that the schistosity and foliation of pre-Cambrian rocks largely originated during static metamorphism rather than during the operation of lateral thrust. It may be observed that neither great volumes nor wide distribution for the alkali-rich rocks would be expected in the older pre-Cambrian terranes by an upholder of the sediment-syntectic explanation of alkaline rocks.

[2] From the composition of the amygdale minerals in the alkaline lavas of Mozambique, A. Holmes (*Nature*, XCVIII [1916], 162) believes the corresponding magmas to have been rich in carbon dioxide as well as undersaturated in silica. The same author describes calcite inclusions in the analcite and nephelite of nephelinite at the Lucalla River, Angola, West Africa (*Miner. Mag.*, XVIII [1916], 64).

more likely cause than the action of the greatly overworked juvenile gases alone.

Migration of free volatile materials from country rock.—The addition of resurgent gas to a magma does not depend entirely on the solution of country rock as such. Elsewhere the writer has emphasized the high probability that connate water and other volatile substances in the country rock may be independently driven into injected magma.[1] An illustration is found in the so-called white traps of Scotland. Day holds that the otherwise typical basalt of the Cheese Bay sill has been reduced, whitened, and rendered vesicular by bituminous emanations from the intruded shale.[2]

Relevant experiments.—Controlled experiments on the chemical effects of dissolving limestone, dolomite, shale, etc., in subalkaline, particularly basaltic, melts are needed. They are sure to be difficult experiments if the conditions of nature are even approximated. Failing such direct tests, the information accruing from certain attempts to extract potash from feldspar commercially is not without value. According to Ross, if potash feldspar, lime (CaO), and water are heated together in a bomb at 300° C. and under a pressure of 91 atmospheres, the potassium is leached from the mineral and, as caustic potash, taken into the water solution. The amount of the leaching depends on the proportion of lime in the mixture until about three grams of lime are mixed with one gram of feldspar, when practically all of the potash is found to be leached.[3] In the same volume where Ross's paper appears (p. 646), R. J. Nestell and E. Anderson illustrate with actual analyses the strong volatilization of both potash and soda in the kilns of cement-mills. They agree with Ross in holding that the presence of lime tends to prevent a recombination of the alkalies with the silica of the original kiln charge.

Such experiments do not, of course, prove anything definite about magmatic reactions, but they do encourage the speculation that, in the presence of juvenile and resurgent water, carbon dioxide, and other volatiles, the alkali oxides may in a sense be

[1] R. A. Daly, *Amer. Jour. Sci.*, XLIII (1917), 445.

[2] T. C. Day, *Trans. Edin. Geol. Soc.*, X (1916), 249, 261.

[3] W. H. Ross, *Jour. Indust. and Eng. Chem.*, IX (1917), 467.

volatilized from a sedimentary syntectic and then concentrated either in the same magma chamber or in satellitic chambers. Whether the necessarily complex solutions will carry the alkalies free or as carbonates, aluminates, hydrates, silicates, or alumosilicates is a problem not now to be solved, but it cannot fail to be considered by the serious student of the assimilation theory.[1]

Perhaps, too, experiment may yet tell the essential reason for leucitic (potash-rich) differentiates in one body and nephelitic (soda-rich) differentiates in another. Leucite, nephelite, and sodalite accompany such minerals as garnet, melilite, hauynite, and plagioclase in industrial slags. It would be of interest to know what contrasts of crystallization there may be in artificial melts, otherwise similar but with pure calcite as the only carbonate flux of the one group of melts and pure dolomite as the only carbonate in the other. Why is albite concentrated in spilite and orthoclase in the "orthoclase basalts"?[2] The reply, that each is due to differentiation, is hardly a reply at all. One needs to know what was the *cause* of each differentiation and *what it was* that differentiated.

BOWEN'S EXPLANATION OF THE ALKALINE ROCKS

Summary of his general theory.—Basing his results on an unmatched group of experiments, Bowen has given to the world a "systematic petrogenic theory" which is deeply concerned with the alkaline rocks.[3] Since the validity of his theory on this side depends on the general mechanism assumed, a considerable amount of attention must be given to main principles before the special reasoning applied by Bowen to the alkaline suite can be properly weighed.

His views may be summarized in his own words (pp. 89, 90): "Consideration of the factors limiting its scope has led to the decision that assimilation is, relatively speaking, an unimportant

[1] Compare G. W. Morey's thorough study of the ternary system, $H_2O-K_2SiO_3-SiO_2$, reported in the *Jour. Am. Chem. Soc.*, XXXIX (1917), 1173.

[2] S. H. Reynolds, *Quart. Jour. Geol. Soc.*, LXXII (1917), 23.

[3] N. L. Bowen, *Jour. Geol.*, Suppl., XXIII, 1915.

factor in the production of the diversity of igneous rocks." He agrees with "the great majority of petrologists" that

> the rocks of any area vary among themselves in a systematic manner which indicates derivation from a common stock through some systematic process of differentiation from that stock.
>
> The decision is reached that this differentiation is controlled entirely by crystallization. The sinking of crystals and the squeezing out of residual liquid are considered the all-important instruments of differentiation, and experimental evidence is adduced to show that under the action of these processes typical igneous-rock series would be formed from basaltic magma if it crystallized (cooled) slowly enough. The characteristic occurrence of basaltic magma as regional dikes and as the material of the great fissure eruptions is considered evidence of the primary nature of basaltic magma. It is concluded, therefore, that most, if not all, igneous rocks have probably been derived from basaltic magma, the processes of differentiation that have been pointed out above emphasizing the lighter, more salic and alkalic differentiates in the upper portions of very large, slowly cooled bodies.

Definition of "differentiation."—On page 3 of his paper Bowen defines differentiation as "any process whereby a magma, without foreign contamination, forms either a mass of rock that has different compositions in different parts or separate masses that differ from one another in composition." In two respects this definition is unsatisfactory.

The word "differentiation" is advisedly and very generally used to mean the actual separation of facies which were once in mutual solution or formed parts of the same body of erupted magma. One cannot postulate initial homogeneity for every erupted magma, nor assume that any heterogeneity a magma possesses has been caused by the break-up of an initially homogeneous solution. For example, if Suess's idea, that crust rocks are fused by juvenile gas rising from the deep, hot interior of the earth, should prove correct for any eruptive center, initial heterogeneity for the new magma would not be improbable. Each part of it might become still more heterogeneous through partial crystallization or other processes, but the original heterogeneity might persist. The rock phases resulting from originally different parts of the magma would be different; they can be called differentiates only by destroying the useful definition of "differentiation" already adopted, expressly or tacitly,

by most petrologists. A similar conclusion follows if any other cause for initial heterogeneity be considered.

Secondly, the term should apply to separations in hybrid magmas, whether formed by the mixture of two or more liquids (Bunsen, Harker) or by the magmatic solution of solid rock (Cotta, many French, Scandinavian, Russian, Australian, and Canadian petrologists). Bowen himself believes in a moderate amount of assimilation. As Loewinson-Lessing has specially insisted, a small degree of contamination with foreign material may change equilibrium in the magma, which therefore separates into strongly contrasted parts. It would be a pity, if it were possible, to exclude a change of the latter kind from the list of those properly covered by the name "differentiation."

Petrologists of the future are, indeed, likely to agree that this word shall be used to denote *separation* of phases and that its definition should be kept free from any presupposition as to the *origin* of the magma which does separate into parts, liquid or solid. Accordingly the units of differentiation may belong to one or more of the following six classes:

1. Contrasted fluid phases of an initially heterogeneous magma, including parts particularly rich in volatile constituents.
2. Solid crystals (fractional crystallization).
3. Mother-liquor left after partial crystallization.
4. Non-consolute liquid fractions (liquid immiscibility).
5. Material of fused country rock, not diffused into the original magma (ultra-metamorphism in part).
6. Original magma locally charged with material dissolved from the country rock, but slowly diffusing from the source of supply (syntexis).

Many field and laboratory observations suggest the control of gravity during the separation in any of the six cases. Given moderate viscosity for the magma, most early-formed crystals should rapidly sink. The formation of these crystals commonly means a decrease of density in the adjacent liquid, which is thus made specifically lighter than the surrounding magma. Such locally generated mother-liquor should tend to rise and concentrate near the roof of the magma chamber. Differential densities must tend

to cause gravitative adjustment among the liquid parts of an originally heterogeneous magma. The parts richest in gas are likely to rise roofward, displacing gas-poor parts of otherwise similar composition. A xenolith of gneiss, melted by, but not diffused into, a moderately viscous gabbroid magma, would rise rapidly and segregate with other melted bodies of the same kind. The most fusible part of the disintegrating xenolith would rise or sink independently. Even if diffused, the more acid foreign material locally lowers the density of the magma, for diffusion is a slow process. On the other hand, the local masses of acidified gabbro will rise quickly if the viscosity of the main body of gabbro is low.

Differentiation of the units described in classes 1, 5, and 6 may take place without any crystallization whatever; that is, all the phases concerned are liquid. Yet in none of the cases is the principle of fluid immiscibility necessarily concerned. The gas, juvenile or resurgent, like the xenolithic gneiss, may be perfectly miscible with the original magma; nevertheless gravitative adjustment is compelled long before homogeneity could be produced by the diffusion of foreign matter.

Whether true liquid immiscibility is an additional, perhaps very important, factor in magmatic differentiation is uncertain. Yet the repeated dogma that this question must be answered in the negative for natural silicate solutions is not warranted. The proper answer awaits the time when the influences of undercooling (by pressure, etc.) and volatile agents, as well as other unknown conditions, are better understood than now.

Bowen has done good service in confirming the view that the diversity of igneous rocks may be partly due to the sinking (or rising) of early-formed crystals in magma, but he has carried the principle farther than it is safe to carry it in the light of present knowledge and in the dark of present ignorance. His definition of differentiation is subjective, since that process is assumed to affect only purely juvenile magma "without foreign contamination." With respect to the biggest problem in petrogeny he thus takes a position which a host of field facts renders untenable. Certain observers ascribe to magma the power to dissolve completely large percentages of country rock. Others, more cautious

in admitting assimilation on the great scale, yet believe a small amount of syntexis to be capable of upsetting equilibrium in a primitive magma and so initiate its marked differentiation. These authors are so fortified with reasons for their faith that it is clearly expedient to keep an open mind concerning syntexis and to define "differentiation" accordingly.

Absence of fractional crystallization in most basaltic sills.—Another general objection to the pure-fractionation hypothesis is that it seems to prove too much. Numberless basaltic (diabasic, gabbroid) sills show by their wide extent that they were comparatively fluent during injection. Presumably the interior portion of each sill of notable thickness remained fluent for some time (hours, days, or weeks) after injection. During this interval the magnetite, olivine, augite, or calcic plagioclase of early crystallization would sink if the basalt regularly behaved like Bowen's crucible melts, on which he so largely bases his theory. Strong differentiation through the sinking of crystals was observed in his artificial melts after these had stood only a few minutes or at most a couple of hours. If, therefore, the experimental analogy were good, the average basaltic sill, five to fifty meters thick and hence slowly chilled, should exhibit differentiation by gravity. According to Bowen's argument, diorites or even quartzose phases might be regularly expected near the roofs and ultra-femic phases near the floors.

These deductions do not match the facts; the chemical homogeneity of most basaltic sills is almost perfect. The gravitative differentiation of basaltic magma is manifestly slow and, in a sense, difficult. Very thick sills, like that of the Palisades of New Jersey, may preserve magmatic life long enough for an appreciable sinking of specifically heavy crystals toward the bottom, but in general it looks as if some "contamination" were necessary before ordinary injected basalt breaks up into contrasted phases. The "contaminating" materials may be either exotic juvenile gas or resurgent gas or liquid.

Comparative homogeneity of femic phases in differentiated sills and laccoliths.—Where gravitative differentiation has taken place in sill or laccolith, the femic phase is commonly rather uniform from top to bottom, except at the layer transitional to the over-

lying, more salic phase. For example, the lower four-fifths of the Pigeon Point sill on the shore of Lake Superior is made up of gabbro. Locally the gabbro does bear interstitial micropegmatite, but from below upward there is no regular increase in this more siliceous ingredient. Such increase is rapid in the thin, overlying, intermediate rock, which is in turn overlain by the thicker, nearly homogeneous roof phase, micropegmatitic granite or red rock. According to the theory under discussion, the quartzose red rock represents the last surviving liquid of basaltic magma from which a correspondingly *large* crop of femic crystals had settled out. At some level between roof and floor these should be specially concentrated. Yet nowhere in the sill is there any important concentration of olivine, pyroxene, or iron oxides beyond the amounts characterizing a normal gabbro. The hypothetical ultra-femic phase is missing, despite the field evidence that the original magma was a rather typical gabbro.[1]

The same is true for at least some of the magnificent sills of the Purcell Mountains, also studied by the writer.

Incidentally, the cooling of a sill undergoing fractional crystallization is seen to be no simple matter. During the formation of a solid crystal, latent heat, estimated as about one-fifth of its total melting-heat, is given off. The fall of magmatic temperature at the level of its growth thus tends to be retarded. The deeper levels to which the crystal sinks share practically none of this latent heat in a direct way. Apart from other causes, the lower layers of the sill magma should therefore freeze first. The level of maximum aggregation of sunken crystals cannot be readily foretold, though it must be above the quickly chilled floor phase of the intrusive.

Origin of the pre-Cambrian granites.—Bowen considers all granite to be a differentiate of basaltic magma. Most of the continental surfaces are apparently underlain by pre-Cambrian complexes, chiefly of granitic composition, though so often metamorphosed to gneiss. If these stupendous masses of granite represent the silicic pole of separation in original basalt, most of the continents must now be underlain, still deeper than the granites, by solid rock much more femic than basalt and of great aggregate volume. Or

[1] Cf. R. A. Daly, *Amer. Jour. Sci.*, XLIII (1917), 423.

else the immense crops of olivine, pyroxene, magnetite, etc., were dissolved in still deeper, very hot magma which may still be liquid. If it is this magma that has been erupted in post-Cambrian time as basalt, then the original magma was not typically basaltic but more salic. On the other hand, there is no field evidence of the assumed generation of ultra-femic differentiates below the pre-Cambrian granite terranes, even if some special mechanism existed whereby the sunken crystals of this early differentiation were arrested at levels above the source or sources of the primitive basalt. Since peridotites, most probably derived from the relatively small volumes of basaltic magma involved in post-Cambrian igneous activity, have been erupted from time to time, it is reasonable to suppose that much more numerous and larger bodies of peridotites should have been erupted during the pre-Cambrian, if the pre-Cambrian granites were differentiated from basalt. The fact is that peridotites are by no means conspicuous in the pre-Cambrian complexes.

As noted elsewhere, the writer is more disposed to regard the basalt of the world as itself a primeval differentiate, the sunken part of an intermediate magma, of which the other risen part is the material now constituting the granitic terranes of the pre-Cambrian.[1]

Rapid transitions between phases of differentiated injections.—Though in each differentiated sill or laccolith the salic and femic phases are generally separated by a layer of rock chemically intermediate between the two, this layer is often very thin. Thus, at Square Butte, Montana, the transitional rock between the syenite and shonkinite of the well-known laccolith is only "a few inches or a foot or so" in thickness. Pirsson describes the transition as "extremely abrupt."[2] Considering the large scale of this differentiation and remembering the distribution of the sunken crystals in Bowen's experiments, such abruptness of transition is hardly to be expected if the differentiation were due merely to fractional

[1] From Bowen's account of the evolution (p. 40) it is not easy to see how the potash of basalt could be concentrated in the proportion seen in granite, assumed to represent the residual liquid of an initially basaltic magma, unless the soda of the granite were much more abundant than the potash; yet in average granite potash dominates over soda.

[2] L. V. Pirsson, *Bull. 237, U.S. Geol. Surv.*, 1905, p. 51.

crystallization.[1] Nor here again does the hypothesis explain the comparative homogeneity of the shonkinite itself.

Origin of quartz diabase.—A difficulty is found also in the nature of that common sill rock, quartz diabase. Table I gives the average composition of twelve typical quartz diabases from various parts of the world (col. 1) and the average analysis of 198 fresh rocks of basaltic composition (col. 2), each average being reduced to 100 per cent.

TABLE I

	1	2
SiO_2	52.34	49.06
TiO_2	1.82	1.36
Al_2O_3	13.70	15.70
Fe_2O_3	5.05	5.38
FeO	8.78	6.37
MnO	0.23	0.31
MgO	4.72	6.17
CaO	8.03	8.95
Na_2O	2.60	3.11
K_2O	1.17	1.52
H_2O	1.56	1.62
P_2O_5	.....	0.45
	100.00	100.00

Typical basalt, like normal diabase, contains no quartz. The quartz diabases mentioned carry 4 per cent to about 20 per cent of that mineral, and varying proportions of biotite, from zero to perhaps 10 per cent. According to Bowen (p. 46) the quartz and biotite have crystallized because the residual liquid, from which pyroxene, calcic plagioclase, and possibly olivine had settled out, became "enriched in alkaline feldspar molecules and water to give a high concentration and consequent separation of most of those molecules which are formed by the breakdown of the alkaline feldspar molecules (biotite or quartz or both)." But the high content of lime and magnesia in quartz diabase shows the amount of sunken pyroxene, olivine, and plagioclase to be very small. In fact, Collins has illustrated quantitatively the fact that much quartz diabase is essentially normal diabase bearing interstitial

[1] Cf. N. L. Bowen, *Amer. Jour. Sci.*, XXXIX (1915), 178 ff.

micro-pegmatite or myrmekite.[1] On the other hand, quartz diabase is characteristically poorer in alkalies than normal diabase or basalt—a relation just the reverse of that expected on Bowen's hypothesis.[2]

Hence, neither the mineralogical constitution of quartz diabase nor its chemical analyses support the idea that its free quartz is due to fractional crystallization, as postulated.

Gas-controlled differentiation in the liquid phase.—That fractional crystallization is only one of several important modes of differentiation is suggested by the activities of magmatic gases. All petrologists recognize the segregation of gas-rich, generally salic, material as magmas complete their crystallization. Assuredly the gases of mobile fractions have been concentrated by the formation of gas-poor, solid crystals. However, one cannot assume a total absence of gas-rich portions in the original magma nor a total inability of resurgent gases to enter the magmatic chamber. If, for these or other reasons, local portions of the magma are or become specially gaseous, these would tend to rise in the chamber and so bring about differentiation independently of crystallization and, it may be, long before crystallization has begun.

The writer has emphasized the possible derivation of augite andesite from basalt by the sinking of crystals. The abundant gas which streams through the vents where augite andesite is generated doubtless lowers the temperature range of consolidation and thereby lengthens the time interval during which crystals may settle. It may also act as a vehicle for the moderate concentration of silica and alkalies in the pipes and thus accelerate the development of a magma contrasted with the original basalt.[3] Lawson expressed a somewhat similar idea in discussing the more salic central parts of the differentiated diabasic dikes around Rainy Lake.[4] This conception does not necessarily imply any degree of immiscibility between the gas-rich and the gas-poor phases of the liquid. It is

[1] W. H. Collins, *Memoir 95, Geol. Surv. Can.*, 1917, p. 96.

[2] See R. A. Daly, *Igneous Rocks and Their Origin* (New York, 1914), p. 321.

[3] Cf. R. A. Daly, *ibid.*, p. 377. That anorthositic differentiation takes place under contrasted conditions is noted on p. 328 of the same book.

[4] A. C. Lawson, *Amer. Geol.*, March, 1891, p. 160.

founded on the slowness of diffusion, a process so sluggish that homogeneity cannot be established or re-established before those phases have been separated by gravity or other forces.

Question of liquid immiscibility.—Bowen decides against the hypothesis of liquid immiscibility as a condition for the splitting of silicate fractions. His chief reason is the negative evidence of experimental melts and of glassy lavas; in neither case have immiscible globules been detected, though the artificial or natural quenchings have taken place at all stages in the cooling histories. In spite of such observations, even on melts "in bombs under high pressure of water-vapor," one cannot but question whether melt or lava flow truly represents the controlling conditions in a great, *quiet*, magma chamber. There, at pressures of hundreds or thousands of atmospheres, the magmatic life is to be measured in weeks, months, years, or centuries. Bridgman's work indicates the probability of the great undercooling of such a magma by pressure. Kuenen has proved that for some liquids pressure raises the critical temperature of unmixing, for other liquids the reverse.[1] Is immiscibility among silicate solutions developed by undercooling through pressure? Further, are the possibilities of the colloidal state for silicates at continued high pressure sufficiently understood? Until these and kindred problems are solved a definite denial of liquid unmixing in magmas should be postponed.

Bowen's second reason for rejecting that principle is found in the high melting temperatures of olivine, magnetite, and other components of monomineralic rocks. Temperatures so high cannot be easily, if at all, assumed for most magmas. Yet it is not ascertained that the phase which has separated was pure olivine, magnetite, or any other of the minerals forming the actual monomineralic mass. The temporary dissolving of a very small proportion of hydrogen, oxygen, or water in any of these substances gives the solution a lower temperature of consolidation than that of the corresponding gas-free phase. The writer has long realized the difficulty of crediting all the observed serpentinization of dunites

[1] P. W. Bridgman, *Proc. Amer. Acad. Arts and Sciences*, XLVII (1912), 530; *Physical Review*, III (1914), 182; *ibid.*, VI (1915), 14; J. P. Kuenen, *Phil. Mag.*, VI (1903), 637.

to ordinary weathering or to the action of seepage waters. Possibly much of the alteration is due to magmatic water. Similarly the segregation of the Kiruna magnetite in a liquid phase was perhaps possible because that phase temporarily carried appreciable amounts of oxygen, water, or other gases.

Whatever values these surmises may have, neither the field relations nor the microscopical petrography of a dunite or of the Kiruna magnetite seem to be compatible with the idea that either rock type is a "raft" of accumulated crystals. The writer believes, therefore, that it is wise to keep the hypothesis of liquid unmixing as still one of the competing explanations in these two cases also.

Failure of sufficient allowance for magmatic assimilation.—The difficulty of excluding syntexis as a significant general process may be illustrated from a field where Bowen himself has worked. In 1910 he concluded that the granophyre at the roofs of several diabasic sills in the Gowganda district, Ontario, is to be referred to the solution of the invaded sediments.[1] Later he wrote:

> This opinion was arrived at principally because of the difficulty of picturing any process of pure differentiation whereby a quartzose rock could be formed from basaltic magma. With this difficulty removed the writer has no hesitation in concluding that the granophyre and the micropegmatite interstices of the diabase were formed after the manner detailed in the present paper [fractional crystallization of pure basalt] and that interchange of material between the granophyre and the adinolized sediment was a subsidiary process contributing to the soda-rich nature of the border phases.[2]

Since 1910 Collins has studied the sills of the same district in detail, proving that granophyric (micropegmatitic or myrmekitic) material has resulted from the interaction of the diabasic magma and the invaded quartzite, etc.[3] Though Collins is conservative in theorizing about the origin of the main granophyric bodies, his evidence agrees with the findings of Bayley, Lawson, and the writer at Pigeon Point, and with the first field impression of Bowen in Collins' field. In view of the close analogy between granophyre and granite the agreement is significant.

[1] N. L. Bowen, *Jour. Geol.*, XVIII (1910), 658.

[2] *Ibid.*, Suppl., XXIII (1915), 49.

[3] W. H. Collins, *op. cit.*, pp. 60, 90. See especially the remarkable photograph in Pl. VIII, *A*.

Differentiation a reversible process.—Tolerance toward the idea of assimilation ought to be specially easy for petrologists who have studied the proofs and processes of differentiation, for differentiation is reversible. This is shown in a variety of ways: First, the original formation of the unstable melt means the former existence of conditions compelling the thorough, mutual solution of all its components. The local re-establishment of those conditions would lead to the re-solution of phases once separated from the original magma. Secondly, the resorption of phenocrysts is a very common proof of re-solution and that on a large scale. The crystals forming early in artificial melts are often resorbed before equilibrium is reached. Salt and cold water saturated with salt make a stronger brine at higher temperature. Can hot, primary basalt fail to dissolve some of the heterogeneous substances of the earth's crust with which it makes contact during and after eruption? Thirdly, because the order of eruption is roughly parallel to that of crystallization, and for other reasons, the temperatures of differentiation are to be considered as relatively low. Higher temperature should, then, presumably tend to restore homogeneity. Finally, the solution of older gabbro in the red-rock magmas, shown at Pigeon Point, Duluth, near Nordingrå, and elsewhere, proves the ability of even a late differentiate to make a new mutual solution with solid rock of essentially the same kind as that now representing the other pole of its own differentiation.[1]

If, then, magmatic differentiation is reversible, assimilation of foreign, solid rocks is seen to be all the more probable. The case of the red rock and gabbro shows that very high temperature may not be necessary for solution; concentration of water is another of the important factors.

Space cannot here be taken for a statement of the many facts (e.g., replacement of invaded formations by batholithic rocks) directly supporting the assimilation theory. They are amply competent to forbid belief that fractional crystallization is the only important cause for the diversity of igneous rocks. Some revision of the subject is called for when Bowen (p. 90) remarks that the

[1] R. A. Daly, *Amer. Jour. Sci.*, XLIII (1917), 442 (footnote); A. G. Högbom, *Geol. Fören. Stockholm Förhand.*, XXXI (1909), 368.

reasons for assuming assimilation on an appreciable scale "are considered to be *entirely* removed when it is shown that the types enumerated above and probably all other igneous rocks *could* be derived from basaltic magma by differentiation alone." A lapse of logic is indicated by the italicized words.

Hybrid rock not the normal result of assimilation.—One must doubt that the "formation of an obviously hybrid rock" should be the "normal result of assimilation" (Bowen, p. 85). A fused xenolith or the solute slowly diffusing away from its source into the dissolving magma tends, as already noted, to rise (or sink) in the general body of liquid. As the foreign material moves under gravity it is more and more mixed with the original magma. This more dilute solution, retaining nearly all of its original temperature, is about as likely to separate as any part of the original magma itself. The special composition of the absorbed rock may of itself stimulate strong differentiation. Under the conditions hybridism is far from being obvious.

The lowering of crystallization temperature by mixture may have little to do with the differentiation of many syntectics. Back of all theorizing are two fundamental questions: How greatly is primary, dissolving magma superheated? What is the ratio of its volume to that of its solute? In other words, how much work is supposed to have been done and what was the amount of energy available?

The petrologist should think always to scale, in space!

Meaning of chilled contacts in batholiths.—Bowen states (p. 84) that little assimilation can be admitted in the case where a batholith has a chilled contact against its country rock. If stoping established the visible contact, the magma was nearly frozen; for, if it had been very hot, further stoping would have occurred. The visible contact was made after the sinking away of the last batch of shattered blocks from the main country rock. The chilling effect is thus due to the relatively low temperature of the new, last surface of contact made with the invaded formation. In that case the chilling phenomena give no trustworthy indication of the assimilating power of the batholith during its enormously long magmatic life.

The petrologist should think always to scale, in time!

Loci of magmatic assimilation.—Again, the importance of batholithic assimilation is to be properly gauged only if all its different loci are kept in mind. In part it is marginal, affecting the roof region and also the vast walls, independently hot, at great depth. For the rest it consists of the fusion or solution of xenoliths, either near the roof or at deep levels. Accordingly batholithic assimilation may be described as:

1. Marginal: (*a*) High-level, (*b*) Abyssal.
2. Xenolithic: (*a*) High-level, (*b*) Abyssal.

Of the four kinds the xenolithic-abyssal and the marginal-abyssal are probably most important. Yet precisely these loci of the geological work, typically very deep, can seldom or never be exposed to view by erosion. Hence batholithic syntexis, beside which all other is an almost vanishing quantity, can be inferred only from its results. Its whole meaning for petrology is not to be directly deduced from visible contacts.

Bowen's special suggestions as to the origin of alkaline types.—The foregoing considerations are vital in the theory of alkaline rocks, but Bowen's petrogenic scheme raises doubts when some of his more specific points are examined. He recognizes two principal modes of origin for the alkaline rocks, as stated in the following quotations from his memoir (pp. 56, 57):

> It has been shown that at the biotite granite stage [of evolving basaltic magma], and to a lesser extent in preceding stages, reactions take place in the liquid whose principal feature is the breakdown of polysilicate molecules, probably under the influence of water, to the simpler orthosilicate molecules, among them $KAlSiO_4$ and $NaAlSiO_4$. The precipitation of $KAlSi_3O_8$, $NaASi_3O_8$, $KAlSiO_4$ in mica, and SiO_2 as quartz means the concentration in the liquid of all the other molecules indicated in the reactions given on pp. 44 and 45. These are principally $NaAlSiO_4$ and the volatile constituents, water, chlorine, etc., with their compounds. If the crystals of the biotite granite stage, including quartz, sink out of this liquid, then the concentration of $NaAlSiO_4$ will finally reach a stage where nephelite will begin to precipitate. There may also result a concentration of CO_2, S, SO_3, Cl, etc., sufficient to cause their precipitation in compounds such as cancrinite, lazurite, hauynite, and sodalite, minerals which are peculiar to nephelite syenites and related rocks. . . . .
>
> Differentiation during crystallization from these very fluid [alkaline] magmas will take place very freely, and the formation of both highly femic and highly alkalic types (rich in feldspathoids) may result. The more "basic"

types of alkaline rocks are not, however, in all cases basic differentiates from nephelite syenite magma. The reactions preliminary to the separation of quartz and biotite begin at an early stage in the crystallization of basaltic magma, and the separation of these minerals may take place at an early stage, giving rise to quartz diorites or granodiorites. The possibility of the formation of alkalic magma at a stage much earlier than the biotite granite stage is thereby introduced if conditions are favorable. Favorable conditions seem to consist in the opportunity for sinking, not only of the plagioclase crystals and femic minerals, but also of the quartz crystals in sufficient amount. Thus may result relatively "basic" alkaline magmas from which such rocks as basanite might be formed, and nephelite syenite itself as a light differentiate.

Assumed desilication by the settling-out of quartz crystals.—The evolution of feldspathoid-bearing magma from the biotite-granite stage is supposed to be accomplished by the separation of crystals of orthoclase, albite, mica, and quartz. A critical element is the actual removal of quartz, and the doubtful nature of this assumption affects the whole argument. In frozen granite, whether a part of a large batholith or wholly constituting a more quickly chilled sill or dike, the quartz is all, or nearly all, interstitial. In the typical case there is no evidence that the quartz crystallized early, so as to be capable of settling-out. Rhyolites do bear phenocrystic quartz, but probably for special reasons. It would be wrong to regard rhyolites as exact homologues to granite in mode of crystallization. In any case the groundmass of rhyolite or quartz porphyry is itself very rich in free silica, and it is difficult to imagine how the groundmass quartz could be removed so as to leave a quartz-free residuum like nephelite syenite.

The same trouble arises in connection with the second postulated method of development, namely, from quartz-diorite or granodiorite magma. The quartz of quartz-diorite and granodiorite is again interstitial and seldom shows any tendency to phenocrystic relations.

Origin of basanite.—Can basanite be derived by the sinking of quartz and other minerals from evolving basalt? Solid basanite has a specific gravity near 2.95. In the liquid state its specific gravity would be about 2.60, a value little if any greater than that of the magma in the immediately preceding stage. On the other hand, the quartz crystals at the temperature of this magma would

have a specific gravity of about 2.54. Obviously the assumption that they would sink at all needs further justification.

The hypothesis concerned faces objections on chemical grounds. Table II gives the average of the analyses of 20 typical basanites (col. 1) and the corresponding averages for 20 quartz diorites (col. 2) and 12 granodiorites (col. 3).

TABLE II

	1	2	3
SiO_2	44.41	59.47	65.10
TiO_2	1.56	0.64	0.54
Al_2O_3	15.81	16.52	15.82
Fe_2O_3	4.66	2.63	1.64
FeO	5.85	4.11	2.66
MnO	0.14	0.08	0.05
MgO	8.20	3.75	2.17
CaO	10.12	6.24	4.66
Na_2O	3.81	2.98	3.82
K_2O	2.37	1.93	2.29
H_2O	2.42	1.39	1.09
P_2O_5	0.65	0.26	0.16
	100.00	100.00	100.00

Inspection of the table shows that the settling-out of "plagioclase crystals and femic minerals" as well as quartz could not produce a basanitic magma from that of either quartz diorite or granodiorite. For instance, the potash should be much higher in the basanite unless it be assumed that much biotite had settled out; but if it had, the iron oxides and magnesia should be proportionately diminished. Yet these components of the femic minerals are much more abundant than in either of the postulated parent magmas. Nor is it likely that the lime could be relatively so much increased in the mother-liquor after the manner suggested, that is, by the sinking (or rising) of plagioclase crystals and femic crystals.

Absence of foyaitic types in most batholiths and stocks.—Again the theory suffers statistically as regards the occurrence of alkaline rocks. If, as Bowen holds, the cooling of a great body of granite magma should normally generate a foyaitic submagma as an end product, then all or most granite batholiths and most of the largest stocks should exhibit foyaitic phases. They do not.

Absence of quartz-bearing lavas in many basalt-trachyte-phonolite volcanoes.—Similarly phonolite should emanate from most old, large volcanoes. Quartzose lavas (quenched, interim phases) should be commonly found in the oceanic volcanoes which are built of phonolite or trachyte and basalt. These expectations also do not agree with the facts.

Eruptive sequence.—In view of the great complexity of the problem not too much stress should be laid on special cases, but it is well to point out a questionable argument relating to the eruptive sequence. Bowen implies (p. 64) that the nephelite syenite-malignite member of the Okanagan composite batholith has its theoretically correct time relation to the other members. On the contrary, the alkaline body is distinctly older than the Similkameen granite batholith, and not younger, as would be naturally expected if the alkaline mass represents the residual liquor of the granite as it crystallized. The neighboring, intensely sheared Osoyoos granodiorite is very much older than the unsheared alkalines, and any direct genetic bond between these two is improbable.

More generally, the writer cannot believe that the world's eruptive sequences support the thesis that foyaites, phonolites, trachytes, etc., are simply the products of the fractionation of pure basalt.

Comparison of basalt and femic, feldspathoid-bearing types.—A formidable array of difficulties with that explanation appears when average basalt (see col. 1 of Table III) is compared chemically with the more femic members of the alkaline suite, such as average nephelite basalt (col. 2), analcite basalt from the Highwood Mountains (col. 3), average leucite basalt (col. 4), average leucite basanite (col. 5), and average theralite (col. 6).[1]

The high lime, magnesia, and iron oxides in cols. 2 to 6 inclusive cannot be reconciled with the hypothesis that the relatively high soda or potash has been developed by the removal of olivine, pyroxene, or calcic plagioclase, or any combination of them, out of an average or typical basaltic magma. The lime content of

[1] Cf. Table II in the writer's *Igneous Rocks and Their Origin*, 1914; and L. V. Pirsson, *op. cit.*, p. 173.

cols. 2, 4, and 5 and the high magnesia of col. 2 are specially noteworthy. On the other hand, this hypothesis does not explain the dominance of potash over soda in cols. 4 and 5, nor the abundant water in the analcite basalt.

TABLE III

	1	2	3	4	5	6
SiO_2	49.06	39.87	47.82	46.47	45.34	45.61
TiO_2	1.36	1.50	0.67	1.33	1.30	1.96
Al_2O_3	15.70	13.58	13.56	15.97	16.59	14.35
Fe_2O_3	5.38	6.71	4.73	5.97	5.83	6.17
FeO	6.37	6.43	4.54	4.27	4.76	4.03
MnO	0.31	0.21	tr.	0.01	0.01	0.19
MgO	6.17	10.46	7.49	5.87	5.43	6.05
CaO	8.95	12.36	8.91	10.54	11.64	9.49
Na_2O	3.11	3.85	4.37	1.69	2.93	5.12
K_2O	1.52	1.87	3.23	4.83	4.55	3.69
H_2O	1.62	2.22*	3.37	2.32	1.12	2.60
P_2O_5	0.45	0.94	1.10	0.73	0.50	0.74
	100.00	100.00	99.79	100.00	100.00	100.00

* Includes 0.29 per cent CO_2.

Perhaps fuller statement of the hypothesis might annul some of the writer's doubts which have been raised by these and other fundamental facts of magmatic differentiation, but at present he fails to see that the mechanism works as it should if the pure-fractionation theory were correct.

Admission of some assimilation by magmas.—Bowen states (pp. 84, 89):

> As a matter of fact, plain evidence is found in the field that magmas do assimilate, especially when they occur in the large bodies commonly termed batholiths. . . . . It may well be, also, that some melilite rocks are formed by the crystallization of a syntectic magma formed by the solution of limestone. . . . . If the absorption of any considerable amount of limestone by a magma can be admitted, it may be expected to have a very unusual effect upon the magma. . . . . The taking of silica from feldspar molecules by the lime and the consequent production of feldspathoid molecules might well be supposed a reasonable possibility. Some alkaline rocks may, perhaps, be so generated.

Yet Bowen believes "that normally the alkaline rocks enter into an eruptive sequence as the products of differentiation solely."

Only a very small addition of foreign lime (1 to 10 per cent) to a large mass of basaltic magma would be necessary to produce

the total amount of desilication observed in any nephelitic or leucitic body yet discovered. Considering the fluxing power of limestone or dolomite on silicate melts, such moderate, local assimilation is surely not improbable. More siliceous sediments or even gneissic or granitic rocks may be simultaneously dissolved; but, on account of its character as a flux, a carbonate rock is likely to be absorbed in greater volume. Hence it does not follow that the solution of "an occasional bed of limestone in a terrane consisting principally of siliceous gneisses . . . . would entail simultaneous absorption of a much greater quantity of relatively siliceous material" (Bowen, p. 63). The relative amounts absorbed must really depend on a number of factors, including the contact relations of each layer of the country rocks to the invading magma.

Meaning of melilitic rocks.—Bowen's admission regarding the melilite rocks is of particular significance when one remembers the exceeding intimacy of alkali-rich rocks with melilite basalt, nephelite-melilite basalt, and alnöite.[1]

Résumé.—The prominent difficulties with Bowen's theory may now be summarized.

The sinking or rising of crystals in magmas is a true cause of diversity in igneous rocks, but it is not the only important cause; perhaps it is much less important than the separation of liquid phases. Apart from the possible development of "liquid immiscibility" in an initially homogeneous magma, separation in the liquid phase is to be expected: (1) if the magma at the time of emplacement in a large chamber were heterogeneous; (2) if for any reason gases are concentrated locally within the magmatic body; and (3) if the assimilation of country rocks, or of their volatile constituents alone, takes place. The field evidences for important assimilation are not consonant with the pure-fractionation theory.

Bowen's theory seems to imply a greater facility of differentiation for basaltic and other magmas than they actually possess; most sills and laccoliths are not visibly differentiated, even though they show features implying fluency after injection. The theory gives no good explanation of the comparatively abrupt transition

[1] See the writer's *Igneous Rocks and Their Origin*, p. 436, and Appendix D.

between the syenite and shonkinite of the Square Butte laccolith, nor of the apparent homogeneity of that shonkinite. It fails to take account of the lack of ultra-femic phases in the Pigeon Point and other sills which display notable salic differentiates. Its consequence, that all monomineralic rocks except certain sulphides are crystal "rafts," may fit the case of anorthosite, but not other cases. Other special objections are found in the chemical nature of quartz diabase, basanite, and the "alkaline basalts." The absence of foyaitic phases in, or apophysal from, most large bodies of granite, granodiorite, and quartz diorite does not agree with the theory as developed. Similarly quartzose lavas, expected on the theory, are not found in many volcanic piles containing trachyte or phonolite with basalt. The lack of quartzose lavas in the enormous and therefore long-lived volcanoes distributed over the main ocean floor is a fact not easily explained by the theory.

Bowen has given the clearest, most detailed argument for the significance of fractional crystallization which has yet been published. His general theory takes cognizance of: the proved genetic association of alkaline rocks with subalkaline magmas, especially the basaltic; the small size of alkaline bodies; their richness in gases and rare elements; the consequent effects regarding grain and variability of composition; the roof positions of alkaline differentiates in many sills, laccoliths, and batholiths; and the concentration of alkalies. Nevertheless, all of these facts are explicable also on the syntectic-differentiation hypothesis, which does not encounter certain difficulties facing the theory of pure fractional crystallization.

GENERAL CONCLUSION

Thus the study of the geological publications issued since the completion of the manuscript of the writer's *Igneous Rocks and Their Origin* has led him to renewed faith in the general explanation there advanced for most of the alkaline rocks. Several expert field observers have sympathetically entertained the hypothesis of control by the syntexis of basic sediments charged with volatile matter. Evidence for the derivation of alkaline rocks from subalkaline magmas has been still further accumulated. Some authors have expressed a degree of confidence that basalt is the only primary

magma eruptible since the end of pre-Cambrian time. Foye has made an extraordinarily important contribution in showing the vast quantity of alkaline solutions which may emanate from granite invading a limestone terrane. Like Allan he has given new, good evidence of the influence of gravity in the separation of magmatic phases. Foye corroborates the decision of Adams and Barlow as to the syntexis of limestone and granite in a complex now famous for its nephelite syenites. Quensel's discovery of an analogy to Alnö in the Almunge district and of the peculiar abundance of vesuvianite in the Almunge canadite is likewise to be particularly recorded. The arguments presented by Cross, Marshall, Richards, and others against the sediment-syntectic explanation of the alkaline rocks are seen to be inconclusive.

Shand finds the syntexis of limestone a partial explanation of undersaturation in igneous rocks. Smyth's view concerning the alkaline series is not acceptable, on the ground that he fails to show cause for the local and exceptional assembling of alkaline elements from subalkaline magmas, assumed by him to be purely juvenile. Experiments by Ross and other students of the commercial-potash problem show the power of lime to volatilize the alkalies from feldspathic or clay mixtures, even at comparatively low temperature.

Certain aspects of Bowen's comprehensive theory have been studied. Serious doubt adheres to some of his fundamental postulates, summoned to explain the descent of alkali-rich rocks from subalkaline magma. On the other hand, many features of his excellent paper must receive hearty commendation from all thinking petrologists; in masterly fashion he has indicated many new, important lines of thought and research.

CONDITIONS OF DEPOSITION ON THE CONTINENTAL SHELF AND SLOPE

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INTRODUCTION

Undoubtedly deposition of sediment has gone on around the margins of the continents in all ages, forming thick accumulations which have encroached upon the ocean basins. To what extent such marginal accumulations have been later uplifted and thus added to the continents may be a matter for difference of opinion; but, though in some parts of the world the sedimentary rocks represent mainly deposits in interior epicontinental seas, there are other parts—the New Zealand area, for example—in which the nature of the rocks indicates that the sediments of which they are

formed accumulated marginally to, rather than upon, one of the continental protuberances.

The subject of marginal sedimentation is closely connected with considerations as to the form and origin of the continental shelf. While this is recognized by geologists and implied by many in their writings it is not usually explicitly stated.

OPINIONS AS TO THE MODE OF FORMATION OF THE CONTINENTAL SHELF

There is a very striking contrast normally present between the gentle slope of the continental shelf and the relatively steep descent, known as the continental slope, from the edge of the shelf to the depths of the ocean. In textbooks this is pointed out, but an explanation of it is generally avoided.

Lake,[1] however, has included a discussion of the problem. In Lake's textbook and in a recent paper by Gardiner[2] several hypotheses bearing on the subject are formulated. From both the reader receives the impression that, if a hypothesis of glacial deposition be put aside as of local application, there remain in the field to account for the continental shelf in low latitudes two rival hypotheses or groups of hypotheses behind each of which there is an equal weight of authority—namely, a hypothesis of erosion with or without subsidence of the eroded surface, and a hypothesis of accumulation according to which the shelf has grown owing to deposition of sediment. It is clear, however, that both these writers favor the hypothesis of accumulation and regard the shelf as for the most part a built feature.

The acceptance of this view is the basis of many geological writings, such, for example, as an article by Chamberlin on "The Ulterior Basis of Time Divisions . . . . ,"[3] in which it is taken as axiomatic that the shelf is formed partly by cutting but mainly by deposition. The same point of view is implied by the use of such terms as "continental delta" by Gulliver,[4] signifying conti-

[1] P. Lake, *Physical Geography* (Cambridge, 1915).

[2] J. Stanley Gardiner, "Submarine Slopes," *Geog. Jour.*, XLV (1915), 202–19.

[3] T. C. Chamberlin, *Jour. Geol.*, VI (1898), 449–62; also Editorial, pp. 424–26.

[4] F. P. Gulliver, "Shoreline Topography," *Proc. Amer. Acad. Arts and Sci.*, XXXIV (1899), 176.

nental shelf, "built terrace" by Gilbert and others, and "topset," "foreset," and "bottom-set beds" by Chamberlin,[1] who thus establishes the analogy of the continental shelf with deltas.

Some clear statements have been made as to the origin of that portion of the continental shelf fringing eastern North America. Willis writes as follows:

> The plateau is composed of sands which are indeed fine near the eastern edge, yet are distinctly granular and incoherent. But soundings on the steep slope beyond the 100-fathom line have brought up very fine silt from the bank of which that slope is the surface, and this silt passes at its foot into globigerina ooze. The zone of transition from clean sand to silt is as sharp as the edge of the slope and is coincident with it. It is evident that the suspended mud which escapes beyond the estuaries and sounds of the littoral is swept out until the undertow expands over the edge of the escarpment, and is diffused in deep water; there the silt forms a great bank 10,000 feet high, with a slope of 3 to 8 degrees, which has grown seaward during geological ages, and continues to expand as erosion continues on the land.
>
> The structure of this deposit can only be inferred, but it is worthy of consideration. The surface of accumulation, to which bedding planes are probably parallel, is inclined at a considerable angle, and traverse the bank from top to bottom obliquely to the vertical thickness. The direction of the growth is outward, not upward. The conditions of deposition are similar to those of a delta advancing into fresh water, and the structure of the deposits is probably similar to that shown by Gilbert for a fresh water delta.[2]

The generalization by the same writer that "the ocean basins are now somewhat overfull . . . . not large enough to hold all the waters, which therefore extend over the margins of the continents,"[3] does not necessarily contradict the foregoing; but it omits to state that, though the growth may now be outward only, during the postulated overflow of the oceanic waters the shelf must have maintained itself by upward growth.

Barrell, also, writes as follows:

> Ocean waves are known to have a perceptible effect to a depth of about 100 fathoms, planing away the shore and the higher parts of the bottom, carrying the products of fluviatile and marine erosion outward to deep water.

[1] T. C. Chamberlin, "Diastrophism and the Formative Processes. VI. Foreset Beds and Slope Deposits," *Jour. Geol.*, XXII (1914), 268–74.

[2] B. Willis, "Conditions of Sedimentary Deposition," *Jour. Geol.*, I (1893), 497–98.

[3] B. Willis, "Principles of Paleogeography," *Science*, N.S., XXXI (1910), 241–60 (see p. 244).

The waves move material along the bottom and prevent the settling of the finest silt until the limit of wave action is reached. Beyond that limit the bulk of the material is rapidly deposited from suspension. In protected situations this depth becomes less and in many places is not over fifty fathoms. There is thus built outwards around the continents a subaqueous terrace, its top gently sloping to a depth of 100 fathoms or less, its front much steeper in comparison, and giving sharpness to the continental margin.[1]

Unqualified support of any hypothesis which assigns the formation of the shelf entirely to erosion is rarely met with. In an explanation of the shelf given by Mill,[2] however, marine erosion with stationary sea-level is given first place, and even in an American textbook submergence of a plain "worn to low relief" is the only explicit explanation given.[3] That this statement does not really express this author's view is shown, however, by the following passage, which appears on another page in an explanation of coastal plains (p. 508): "Off the eastern coast of United States there is a level sea-bottom plain, known as the *continental shelf*. . . . . If there should be an uplift of 600 feet, this very level plain would be added to the continent. . . . . It would be underlain by unconsolidated sediments."

The following clear statement on the subject by Gilbert and Brigham is also worthy of attention as an emphatic refusal of support to the hypothesis of submergence of a plain of erosion:

It will be remembered that the resemblance of Chesapeake Bay to a branching river was explained by saying that the Coastal Plain had sunk down so as to let the sea flow into the Susquehanna Valley. Because we now point out that the plain is an old sea-bed which has risen, it must not be thought that one fact contradicts the other. Both changes have taken place, but at different times. After the plain had been formed under the sea it was lifted so high that rivers dug deep valleys across it; then it was lowered part way, to the present height.[4]

A somewhat similar statement from Chamberlin and Salisbury may be quoted: "Almost nowhere does the real edge of the con-

[1] J. Barrell, "The Upper Devonian Delta of the Appalachian Geosyncline," *Am. Jour. Sci.*, XXXVI–XXXVII (1913–14), 249.

[2] H. R. Mill, *The Realm of Nature* (2d ed.; London, 1913), p. 219.

[3] R. S. Tarr, *College Physiography* (New York, 1914), p. 641.

[4] Gilbert and Brigham, *An Introduction to Physical Geography* (New York, 1902), p. 153.

tinent appear above the ocean. . . . . A continuous shelf almost universally borders the continents. . . . . The continent was recently so deformed that these shelves were out of water," and, on a later page: "The continental shelf . . . . may be supposed to have been built out upon the border of the sea-basin by progressive sedimentation."[1]

The meaning of all these writers is clearly that a *continental shelf*—a *constructional* feature, built of marine sediments—has been uplifted and dissected and then resubmerged.

In textbooks the statement is frequently made that the true boundary of a continent is situated at the outer edge of the continental shelf—the "continental edge" of Murray—rather than at the shore line.[2] At first sight this reads like a negation of the view that the shelf is mainly a built feature of recent growth. Such statements seem, however, generally intended merely to convey the information that, when mean slopes of the earth's surface are plotted as a hypsographic curve, there is a sharp change of average slope at the depth of the edge of the continental shelf but none at sea-level.

THE PRESENT-DAY SHELF LARGELY CONSTRUCTIONAL

Since "rival" hypotheses of *erosion*, marine and subaërial (followed by subsidence), and *deposition* have been put forward by Lake, Gardiner, and others, it is necessary to examine critically the consequences of each.

The hypothesis that marine erosion is alone responsible for the formation of the continental shelf.—Undoubtedly wave action is capable of eroding, not only at the shore line, but at considerable depths, wherever the ratio of the waste supply to the transporting power of the sea is sufficiently low to permit parts of the rock bottom to be swept clean, and where there is at the same time sufficient movement of the water to move particles of appreciable

[1] Chamberlin and Salisbury, *Geology*, III (New York, 1906), 521, 526.

[2] The shelf is described, for example, as "submerged parts of the continental protuberance" (R. D. Salisbury, *Physiography*, p. 22), and it is stated that "the area between the actual shore and the 100-fathom is regarded as belonging to the continents, though at present overflowed by the sea" (Hatch and Rastall, *The Petrology of the Sedimentary Rocks* [London, 1913], p. 11).

size across the exposed rock. This is an accepted principle. Wave motion extends, it is believed, to a depth of about 100 fathoms in the open ocean; it has been shown to be sufficiently strong to move gravel at a depth of 36 fathoms.[1] There is thus no reason to believe that, *if the bottom were kept swept clear of sediment*, erosion could not take place—though, obviously, the slowness of erosion would increase with depth—as far seaward as the edge of the shelf in 100 fathoms, at which depth there would be an abrupt change of slope from that of the shelf to that of the initial sea floor. This is the gist of the hypothesis as put forward by Mill and by Lake. The postulate of submergence following the cutting of the platform introduced by Gardiner is unnecessary.

The question arises whether clean sweeping of the cut platform such as is postulated in the preceding paragraph is possible; and it would appear that such a state of affairs must be extremely uncommon if it ever occurs. In the ordinary case deposition of the waste produced by the cutting of the platform, together with the supply from the neighboring land, must take place seaward of the area in which erosion is taking place. It is indeed obvious, as has often been pointed out, that the observed continental slope must be the surface of the last-formed layer of this sediment and represents more or less accurately the slope at which it came to rest. It seems highly probable that earlier-formed layers came to rest at the same inclination, and that some portion of the shelf is everywhere composed of such inclined layers.

The combined processes of erosion and deposition have been shown by Davis[2] and by Fenneman[3] to produce a "graded profile" or "profile of equilibrium" from the shore to the edge of the shelf, which is a fairly even slope though somewhat concave near shore and convex seaward. Fig. 1 illustrates the growth of a shelf by this combination of erosion and deposition. It will be seen that,

[1] A. R. Hunt, "Formation of Ripple Marks," *Proc. Roy. Soc.*, XXXIV (1882), 1–13 (see p. 10).

[2] W. M. Davis, "The Outline of Cape Cod," *Geographical Essays* (Boston, 1909), pp. 690–724 (see pp. 700–703).

[3] N. M. Fenneman, "The Profile of Equilibrium of the Subaqueous Shore Terrace," *Jour. Geol.*, X (1902), 1–32.

while, as the shore line recedes, erosion of the sea bottom must go on near shore, as the shelf front advances the graded profile is maintained farther seaward by deposition.

The stream of waste in transit seaward will generally, on account of its slow movement, form a thick layer on the outer part of the shelf precluding the possibility of erosion of the deeper layers of strong currents along the shelf, so that the built portion of the shelf may be narrow compared with the cut portion. In such a case erosion must extend into relatively deep water, parts of the eroded sediment or of the rock floor. It is, however, conceivable that in exceptional cases much or all of the waste may be swept away by

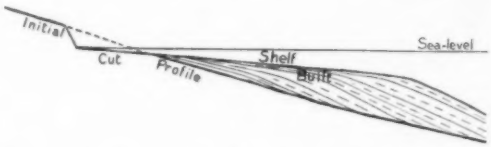

FIG. 1.—Diagram to illustrate the formation of a continental shelf by marine erosion and deposition.

floor of bedrock being occasionally swept clean. In this way are perhaps to be explained some recorded occurrences of hard bottom far out on the continental shelf.

The modification of this hypothesis which requires subsidence following marine planation has nothing to recommend it. Fig. 2*a* is a copy of the figure used by Gardiner in illustration of the hypothesis, modified by the addition of a thick layer of sediment (coarsely stippled) on the top of the cut platform, which must be added to restore a normal profile. The profile of a later stage of a shelf developed by cutting and building on this initial form is also added (lightly stippled).

The hypothesis that subaërial planation followed by submergence explains the continental shelf.—In considering this possible mode of shelf formation care must be taken to exclude cases of temporary emergence of a shelf already formed. References to portions of the shelf thus temporarily uplifted, partially dissected, and again submerged have been already quoted; and oscillations of the

continental borders, if not of all land surfaces, are known to be of common occurrence.

Rapid submergence of a peneplain would undoubtedly result in the formation of a sea bottom of small relief with a general seaward slope; but it is impossible to imagine a peneplain the level surface of which would, in the period preceding submergence, end abruptly at the shore line with a sharp transition to a steep slope into the adjacent ocean basin. Even if such a state of affairs were possible, it would be necessary, in order to account for the formation of the

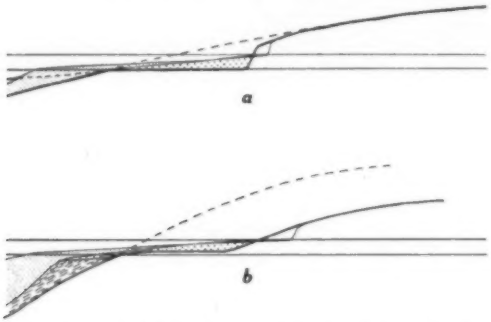

FIG. 2.—Diagrams copied from those used by Gardiner to illustrate theories of shelf formation, with additions showing the development by deposition of a profile of equilibrium.

continental shelf in this manner, to postulate a submergence of all the continental margins to the same extent, about 600 feet, and in most cases to disregard entirely the evidence afforded by the geomorphology of coastal lands as to their erosional and deformational history. A submerged peneplain could not be expected to provide, ready made, a graded subaqueous shore profile. Upon an initial surface so formed wave action would immediately come into operation, cutting in some places and depositing in others; and so, even if the initial form of any part of the continental shelf may have been a submerged peneplain, the sequential form which the shelf exhibits today must be ascribed to the work of waves.

The development of a peneplain, moreover, necessitates a very long period of erosion, during which the land mass on which it is

cut remains essentially stationary in level, and during which an enormous quantity of waste is carried to the sea. Such waste will be deposited seaward as a continental shelf of unusually great breadth, and this, when submergence of the peneplain takes place, will subside also. Since, presumably, the edge of the shelf before subsidence will be situated at or just within the 100-fathom line, after subsidence has taken place, when the width of the plain will have been added to that of the former shelf, the composite shelf so formed will extend into water much deeper than 100 fathoms. Upon such a shelf a thick layer of sediment would require to be deposited to reduce the depth at its edge to 100 fathoms; and so it appears evident that submergence of a peneplain without the subsequent co-operation of wave action on an extensive scale is not competent to produce a continental shelf of typical form.

The profiles of the shelf in the diagrams given by Gardiner to illustrate the "formation of the continental shelf by the submergence of an abrasion platform" and "of a land plain" are quite unlike those found in nature. This is perhaps intentional, as that author does not appear to favor either hypothesis. Such initial profiles would be very readily modified by wave and current action, according to the principles deduced by Fenneman.

Two stages of such modification are shown in Fig. 2*b* as an addition to Gardiner's diagram of "submergence of a land plain." The deposit added in an early stage of the modification is coarsely stippled, and that in a later stage lightly stippled.

The hypothesis that the continental shelf is formed as a result of deposition.—The conditions of delta-formation by streams bearing a load of coarse waste into lakes are now well understood chiefly owing to the work of Gilbert,[1] and an extension of the principles established by Gilbert to cover the case of rivers supplying large quantities of finer waste to the ocean has more recently been made by Barrell.[2] It is but a step from the consideration of the

[1] G. K. Gilbert, "The Topographic Features of Lake Shores," *U.S. Geol. Surv., 5th Ann. Rept.*, 1885, pp. 69–123.

[2] J. Barrell, "Criteria for the Recognition of Ancient Delta Deposits," *Bull. Geol. Soc. Am.*, XXIII (1912), 377–446.

submarine portions of deltas, which have been shown by Barrell[1] to cover often a larger area than the subaërial portions and to form large seaward protuberances of the continental shelf, to the consideration of the shelf as a whole.

Off all coasts deposition of a greater or less amount of sediment is always in progress, not only off the mouths of rivers, but along the whole length of the coast lines, and there can be a difference only in degree between such deposition and that by which the seaward, submarine portions of deltas are built forward. In the shallow water near shore conditions may be entirely different from those on the shallow-water portions of deltas; for here, as has already been shown, erosion may be going on, either deposition or erosion being in progress according to the state of balance between waste supply and transportation. Erosion near shore, however, will, generally speaking, merely have the effect of pushing the zone of deposition farther seaward.

From observation of the form and structure of the small deltas laid bare and dissected owing to the lowering of the level of the water in lakes it is known that waste, after being discharged from a river, is transported outward from the shore owing to agitation and forward movement of the water, and traverses the upper, gently sloping surface of the mass of sediment already deposited ("subaqueous plain," Barrell) until, reaching the edge, it slips over into deeper and stiller water and comes to rest at the angle of repose on the more steeply sloping front of the mass ("foreset slope," Barrell). Similarly, in the case of larger deltas of finer waste being built into the ocean, the waste is transported seaward across a subaqueous plain which is essentially a part of the continental shelf, extending outward to the depth at which the bottom is no longer sensibly stirred by wave action ("wave base," Gulliver[2]). This depth in the open ocean is clearly indicated by the

[1] *Op. cit.*, Fig. 1, p. 388; "The Strength of the Earth's Crust," *Jour. Geol.*, XXII (1914), 39–42.

[2] F. P. Gulliver, "Shoreline Topography," *Proc. Amer. Acad. Arts and Sci.*, XXXIV (1899), 176–77. As defined by Gulliver wave-base, the limiting plane toward which marine erosion will tend to lower the wave-cut platform, is "the depth to which the maximum wave action is possible." The term has been redefined by Fenneman as the depth "at which wave action ceases to stir the sediments" (N. M. Fenneman, "Lakes of Southeastern Wisconsin," *Wis. Geol. and Nat. Hist. Surv., Bull. No. 8*, 1902, p. 25).

"mud-line" of Murray and Renard, which, according to Murray, is situated at a depth of about 100 fathoms.[1] On the slope below this depth the finest particles of sediment "come permanently to rest on the bottom." Beyond the mud-line is the steeper foreset slope on which even the finest waste can come permanently to rest; but the foreset slope is much less steep and the transition to it from the subaqueous plain much more gradual than in the case of the small deltas of coarse material in lakes. For one thing water-logged mud will not remain at rest on any but very gentle slopes, and, as Barrell points out, "where, as in the case of large rivers, the detritus is mostly fine in texture, the foreset beds are built largely by material settling from suspension." The foreset beds, in which sediment swept outward along the bottom is mixed with what has settled from suspension, grade into the bottom-set beds or pelagic deposits built entirely of material settling from suspension.

In the case of portions of the continental shelf remote from the mouths of large rivers the mode of accumulation must be essentially the same as in deltas; but there will generally be present in the waste supplied from the land a much smaller proportion of the fine mud particles resulting from subaërial weathering. No doubt much of the material broken by wave attack on the shore line and supplied by smaller rivers becomes very finely comminuted in its long passage across the shelf; but the absence of a large body of mud sufficiently fine to be carried far seaward in suspension is reflected in a sharper transition from the continental shelf to the continental slope, and in a steeper inclination of the latter than is found in delta fronts. Thus the structure of the continental shelf may be regarded as presenting generally a closer resemblance to that of the subaqueous portions of small lake deltas than is shown by the corresponding portions of the deltas of great rivers.

The materials of which the shelf is being built forward are known from samples taken by oceanographers from the last layer added. These deposits on the continental slope fall into the "terrigenous" division of "deep-sea deposits, beyond 100 fathoms" in Murray and Renard's classification of marine deposits,[2] and the

[1] Sir John Murray, *The Ocean* (Home University Library), (London), p. 202.

[2] "Deep-Sea Deposits," *Report of the Scientific Results of the Exploring Voyage of H.M.S. "Challenger," 1873–76* (London, 1891); Murray, *The Ocean*, p. 201.

most common types bordering continental coasts are "blue mud" and "green mud." Examination of the samples shows that the muds have been subjected to chemical changes on the sea bottom, but that they retain their original characters sufficiently to show that the material has been derived from the land.

> As a rule they are heterogeneous from the admixture of larger or smaller rock and shell fragments. . . . . Rock fragments and mineral particles may make up as much as 75 per cent in some cases, the most characteristic species being quartz; the usual proportion of mineral particles is about one-fourth of the whole deposit. Amorphous clayey and muddy matters are always abundant, the average percentage being about 60, generally increasing in amount with greater distance from the land.[1]

Deltas and a more or less continuous shelf of typical form may be produced artificially on a small scale in a laboratory experiment, the apparatus for which has been described,[2] but, while such experiments serve admirably their purpose of illustration, it is obvious that quantitative results bearing on the relation of the depth of the edge of the shelf to wave-base would be difficult to obtain. As Davis remarks, "In most problems of geology and geography experiments have rather an illustrative than a demonstrative value."

It has often been pointed out that the edge of the continental shelf is situated everywhere (off exposed coasts) at a constant depth of about 100 fathoms, that is to say, at the greatest depth to which the water is stirred by wave action. As a matter of fact the 100-fathom line is situated generally at about the center of a convex curve to which the gentle slope of the continental shelf is tangent and which passes into the more steeply inclined surface of the continental slope. The slope begins to steepen usually from a depth of about 70 fathoms, at which depth it would seem that the effects of wave action are becoming extremely feeble.

This constant depth of the "continental edge," together with the fact that a shelf borders, with rare exceptions, all the coasts of the world whatever their origin, whether by regional uplift or subsidence, by warping or by faulting, is of great significance (see Fig. 3).

[1] Murray, *The Ocean*, p. 203.

[2] R. S. Tarr and O. D. von Engeln, "Representation of Land Forms in the Physiography Laboratory," *Journal of Geography*, VII (1908), 73–85.

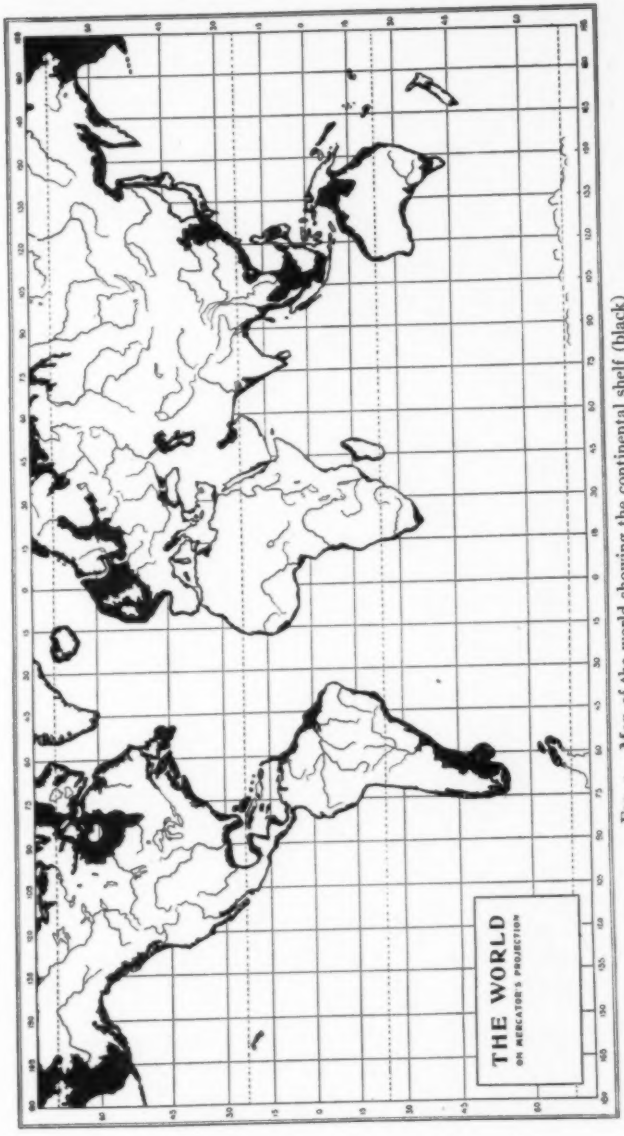

FIG. 3.—Map of the world showing the continental shelf (black)

It indicates that the present-day shelf has taken form since sea and land assumed their present relative levels,[1] and therefore that the molding of the shelf is geologically a very recent event; for most coastal lands afford evidence of considerable movements either of uplift or of subsidence having taken place at a not very distant date.

Nansen,[2] reasoning from the same data, comes to a very different conclusion. While he recognizes the practical uniformity of level of the edge of the continental shelf, he argues from the assumption that the shelf is an ancient feature and makes the remarkable deduction that, though great changes of level have taken place, which in at least some cases he regards as movements of the land rather than of the ocean, the continental margins have everywhere returned to their ancient level.

A general idea of the width of the continental shelf is given by Fig. 3. More precise data may be obtained from an inspection of ocean charts upon which the 100-fathom submarine contour line is or may be drawn, or more conveniently from the numerous maps in Stieler's atlas which show the 200-meter line. Variation in width depends on several factors; no doubt the most important is the depth of water into which the shelf has grown outward since the latest movement of the strand. If the vertical movement has been small, as, for example, around the British Isles, the present shelf is a modified older shelf, added to at the margin, and therefore broad.

Another important factor must be the presence or absence of abundant waste from the land, which will be largely determined by the presence or absence of large rivers in the vicinity. Still another must be the time that has elapsed since the latest important movement of the strand.

Variations in the width of the shelf do not affect the question of its essential continuity, which, as pointed out above, prove its capacity for rapid growth and renewal. It is obvious that the

[1] T. C. Chamberlin says of it: "The terrace is as universal (at least in its initial stages) as the sea border and is a necessary consequence of the relations of sea and land" (*Jour. Geol.*, VI [1898], 526).

[2] F. Nansen, "Oscillations of Shorelines," *Geog. Jour.*, XXVI (1905), 604–9.

shelf bordering a recently uplifted coast which has been cut back to a line of cliffs by energetic wave action must, at its landward edge, be a wave-cut platform; but even in this case farther seaward the waste derived from this retrogradation of the shore together with that brought down by rivers while cliff recession was in progress must have been deposited, forming a seaward extension of the shelf in the manner described on an earlier page. Off uplifted coasts the shore lines of which have not retreated an appreciable distance from the initial position, the shelf must be almost entirely constructional, and the same is true in the case of depressed coasts the initial embayed outline of which has not yet been much modified by marine erosion.

THE STRUCTURE OF THE BUILT SHELF

The principle is now well understood that, just as in a river the ratio of load to transporting power determines whether degradation or aggradation shall take place, so along a shore line retrogradation or progradation of the shore occurs according as the waves breaking on the shore are underloaded and hungry or are overloaded with waste from another source.

With the shore line fixed in position.—It will simplify the discussion of the structure of the built shelf if an ideal case is considered first, in which the load and the transporting power of waves and along-shore currents remain exactly balanced during the building of the shelf, so that the shore line neither retreats nor advances. Fig. 4*a* is an ideal section of a shelf built under such conditions. The front of the shelf being situated at the level of wave-base during all the stages of growth, it is clear that for each foreset bed there will be a relatively very thin topset bed, the two being different facies of the same stratum, that the topset beds will thicken seaward, and that successive topset beds will approach more and more nearly to perfect horizontality.

With the shore line advancing.—Fig. 4*b* represents the case in which the waves as they reach the shore are overloaded throughout the whole period during which the shelf is being built. The coast will be continuously prograded, and upon the growing strip of strand plain additional sand from the beach will be piled to form

dunes. The structure of the resulting shelf will be similar to that with stationary shore line with the exception that each (theoretical) foreset bed will have a subaërial as well as a subaqueous portion. In an actual case the stratification will be very irregular in the shoreward portion of the shelf, as there will be much cross-bedding in both the shallow-water and the subaërial deposits.

A very similar result is produced where the shore line advances seaward owing to the growth of an alluvial plain formed by confluent deltas, as, for example, along the coast of the Canterbury Plains, New Zealand. The structure of the whole mass of deposits,

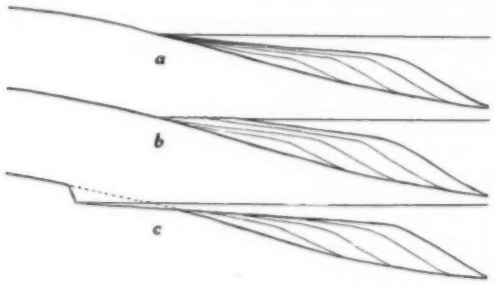

FIG. 4.—Ideal sections across the continental shelf; *a*, the shore line fixed in position; *b*, the shore line advancing; *c*, the shore line retreating.

including the alluvium of which the plain is built and the shelf which fringes it, will be similar to that of the delta of a single river as described by Barrell.

With the shore line retreating.—In Fig. 4*c* the commoner case is represented in which the waves reaching the shore have power to erode and where, therefore, retrogradation of the shore takes place (see also Fig. 1). The shelf will consist of two portions, a cut platform and a built platform, and it is obvious that the ratio of the width of the cut to that of the built platform may vary widely. As has been pointed out on an earlier page, it is theoretically possible that, in exceptional cases, there may be no built platform, the material broken by waves together with that coming from the land being swept away by along-shore currents and the shelf being entirely or almost entirely a cut platform such as that of the

Norwegian coast as interpreted by Nansen. On the other hand, owing to nearness of a large source of supply of waste from the land, the shelf may differ but little from that shown in Fig. 4*a*, there being but little retrogradation of the shore and the shelf consisting almost entirely of a built platform.

Davis, in considering the development of the graded shore profile at Cape Cod,[1] comes to the conclusion that "the critical point, where marine action changes from degrading the near-shore bottom to aggrading the off-shore bottom, migrates seaward." Clearly, however, in the general case, after a continental shelf has been developed, the direction of migration of this critical point will depend upon the relative rates of seaward growth of the shelf and landward retreat of the shore line. When the rate of growth of the built platform is rapid compared with the rate of retreat of the shore line the critical point in the profile will generally migrate landward. In this case no part of the built platform will be subsequently eroded and each topset bed will overlap the preceding one, lying upon and protecting from further erosion a strip of the cut platform. If, on the other hand, owing to rapid shore recession, the critical point migrates seaward, some of the earlier-formed topset beds will be obliquely truncated by the cut platform. While the former case is perhaps the commoner in nature, it is the latter which lends itself to diagrammatic representation, owing to the mechanical difficulty of drawing a broad shelf on a narrow page.

With the shore line alternately retreating and advancing.—The shore-line features of parts of the coast of New Zealand, notably in eastern Marlborough and western Wellington, indicate that, owing to some disturbance of the balance between load and transporting power of waves and along-shore currents, retrogradation and progradation have occurred alternately. Where such alternation is taking place, somewhat complex structures in the topset beds will result. During each period of shore retreat the previously formed topset beds near shore will be eroded, and during each advance fresh topset beds will be laid down unconformably on an eroded surface.

[1] W. M. Davis, *Geographical Essays* (Boston, 1909), pp. 702–3.

LITHOLOGICAL CHARACTER OF THE BEDS

The topset beds deposited during stillstand will constitute such a small proportion of the whole mass of sediment that geologically they will be of slight importance in uplifted shelf deposits. Oceanographic data indicate that the materials of which they are composed vary widely, ranging from gravel and sand to mud, with or without shells. The bulk of the deposit will consist of foreset beds built out over a thinner series of bottom-set beds in which extremely fine particles that have remained a long time in suspension will be present mixed with organic remains. Farther seaward these will grade into pure pelagic deposits.

TABLE I

A = Composite analysis of green and blue muds
B = Composite analysis of 78 shales

	A	B
SiO_2	57.05	58.38
TiO_2	1.27	0.65
Al_2O_3	17.22	15.47
Fe_2O_3	5.07	4.03
FeO	2.30	2.46
MnO	0.12	.....
MgO	2.17	2.45
CaO	2.04	3.12
BaO	0.06	0.05
K_2O	2.25	3.25
Na_2O	1.05	1.31
P_2O_5	0.21	0.17
SO_3	.....	0.65
S	0.13	.....
CO_2	.....	2.64
C	1.69	0.81 (organic)
H_2O	7.17	5.02
Other constituents	0.1964	.....
	99.9964	100.46

Leaving aside volcanic and coral muds, which require special conditions for their formation, we find that, as shown by samples obtained from the continental slopes, blue muds and green sands and muds are the most common materials of the foreset beds, the former where the supply of waste is ample and the latter where the supply is more meager. Both of these are well represented

among the sedimentary rocks known to geologists, the former constituting shale and mudstone and graduating into marl, and the latter being represented by greensand and less pure glauconitic rocks. The samples obtained from the continental slope show well-marked stratification.[1] As Murray remarks: "The analogues of the now-forming terrigenous deposits are to be found in all geological periods."[2]

In this connection an instructive comparison can be made of the chemical analysis of a composite sample of 4 "green muds" and 48 "blue muds" from various parts of the continental slopes with that of a composite sample of 78 shales taken as giving the average composition of the argillaceous sedimentary rocks, but probably not by any means all of foreset origin. The analyses are given by Clarke.[3]

STRUCTURE OF A SHELF BUILT DURING POSITIVE MOVEMENT

Without going into the question of the possible causes of changes in the relative levels of sea and land the fact may be accepted that accumulation of sediment has in the past been very commonly accompanied by positive movement. No doubt positive movement is in some cases a rise in sea-level and in others a sinking of the floor upon which sediments are being laid down, and in still other cases a combination of both of these. It is convenient, however, in an investigation of the probable structure of shelf deposits, to regard all changes in the relation of the shelf to sea-level as vertical movement of the shelf rather than of sea-level. The latter will affect the relation of the sea to the neighboring land also, that is to say, it will be regional in its effects, and obviously precisely similar effects will be brought about by regional subsidence. By regarding the sea-level as fixed and the shelf as subsiding, however, we are able to investigate the effects of differential as well as regional changes of level.

To begin with, it may be supposed that a shelf of moderate dimensions has been built forward during a period of stillstand

[1] Sir John Murray, *The Ocean*, p. 213. [2] *Ibid.*, p. 234.

[3] F. W. Clarke, "The Data of Geochemistry," *U.S. Geol. Surv., Bull. 616*, 1916, p. 514 and p. 28.

throughout which there has been a steady stream of sediment from the land. If now this already formed shelf be supposed to subside very slowly, as the shelf sinks, the stream of waste supplied by rivers from the adjacent land may be reduced in volume, may remain sensibly constant, or may be increased in volume, according as the land subsides also, remains stationary, or is uplifted. Let us suppose, however, that the stream of waste is sufficiently continuous and the movement sufficiently slow to allow the shelf to be maintained during subsidence. Obviously maintenance on a sinking floor of a shelf with its outer edge at a fixed depth (approximately 100 fathoms) below sea-level involves deposition of material on the top of the shelf as well as, or instead of, in front of it. Less of the waste will be available for deposition as foreset beds than in the case of a shelf being built during a period of stillstand. The shelf will be built upward of material arrested in transit seaward owing to its being lowered below the depth at which wave action stirs it sufficiently to keep it in motion.

This accumulation of topset beds may attain an enormous thickness, as has been shown by Barrell to be the case in deltas, the thickness depending only upon the amount of subsidence during which a continuous supply of waste is kept up.

Assuming that during subsidence the supply of waste is always sufficiently abundant to insure the continuity of deposition of topset beds over at least a portion of the area, we may investigate the conditions of deposition of topset beds, foreset beds, and pelagic deposits, understanding by the latter term deposits formed either in moderatly deep or relatively shallow water where the supply of bottom waste fails, the deposit consisting of organic and minute inorganic particles settling from suspension ("flotation beds," Chamberlin).

The form of a single *stratum* deposited in a given time during stillstand will be that shown in Fig. 5*a*, that is to say, the bulk of the terrigenous sediment will be in the foreset portion, the edge of the shelf advancing seaward a considerable distance during the given time. With continuous subsidence in progress, however, the formation of thick topset beds may use up so much of the waste that there is little or none left to build the edge of the shelf forward.

If there is still a small advance there will be a terrigenous foreset bed, but it will be relatively thin (Fig. 5*b*). It is only a step from this case to one in which there will be no terrigenous foreset bed, the waste being just sufficient or even insufficient to build a topset bed for the full width of the built shelf, the edge of the shelf in the latter case retreating landward. In no case, however, will the continuity of a stratum be broken, for, if the foreset bed fails, the pelagic deposits will extend up the continental slope to join the topset bed (Fig. 5*c*).

During long-continued subsidence, the duration of which may be comparable with the length of a geological period, the movement

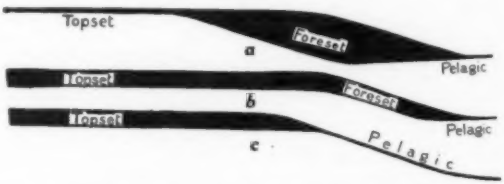

FIG. 5.—*a*, Variation in thickness of a stratum deposited during stillstand; *b*, a stratum deposited during subsidence with abundant supply of waste; *c*, a statum deposited during subsidence with restricted supply of waste.

is probably never absolutely uniform and continuous. The geological record affords evidence to the contrary, and what is known from physiographic evidence of the more recent movements points in the same direction. Oscillations being left out of account, consideration may be given to the consequences of fluctuations in the rate of subsidence. Clearly, with a constant rate of supply of waste, alternating periods of extremely slow and relatively rapid subsidence may determine alternating advances and retreats of the edge of the shelf. It is obvious also that, with slow subsidence at a uniform rate in progress, fluctuations in the supply of waste may produce similar results. Increase in the supply of waste may result from differential elevation of a portion of the neighboring land mass, after which a falling off will take place as a result of regional subsidence or peneplanation of the land, to be followed by a further increase when differential elevation is renewed, and so on.

The effects of fluctuations in the rate of subsidence of the sea floor and in the rate of supply of waste may be considered together. When the ratio of waste supply to rate of subsidence is sufficiently large the front of the shelf will advance (Fig. 6, *B*); and when this ratio is sufficiently low the front will retreat (Fig. 6, *C* or *D*).

Notable fluctuations in the value of the ratio will determine alternating periods of advance and retreat, and these alternations will produce interstratification of beds of very varied lithological character in the shelf deposits which are not without parallel in the known rocks.

In the landward portions of the shelf intercalations of subaërially deposited material may be present in the dominantly marine topset beds, as Barrell has shown to be the case in those portions of

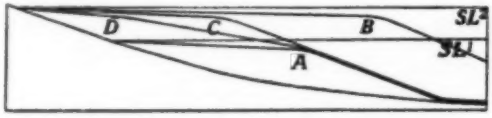

FIG. 6.—Diagram illustrating the growth of a shelf during a period of subsidence. *A*, edge of the shelf with sea-level SL^1; *B*, *C*, *D*, possible positions of the edge of the shelf with sea-level SL^2.

the shelf which are the submarine portions of deltas.[1] An instructive example of such alternation has recently been described by Stebinger.[2]

Farther seaward the mass of sediment deposited during subsidence may be for a considerable distance composed of marine topset material throughout. The texture of these topset beds will depend very largely upon the relief and also upon the nature of the rocks of the neighboring land; and it may be expected to vary vertically, fine sediments marking periods when the land has been reduced to low relief by erosion and coarser sediment marking periods of renewed differential elevation. The topset material will

[1] J. Barrell, "Relative Geological Importance of Continental, Literal and Marine Sedimentation," *Jour. Geol.*, XIV (1906), 353–54, Fig. 10, p. 445; "Criteria for the Recognition of Ancient Delta Deposits," *Bull. Geol. Soc. Am.*, XXIII (1912), 399, Fig. 4.

[2] E. Stebinger, "The Montana Group of Northwestern Montana," *U.S. Geol. Surv., Prof. Paper 90G*, 1914, pp. 61–68.

not, in general, be subjected to very prolonged chemical and mechanical disintegration on the shelf before being buried. When sandy it may contain, but little altered, grains of the less stable minerals of the shore rocks. If these rocks are predominantly igneous the topset sands when consolidated may form arkose or greywacke, similar to that forming the great bulk of the strata in the mountain ranges of New Zealand. Of these rocks, commonly ascribed to the Maitai System, Marshall writes:

> The material of which all these rocks is composed has been derived from plutonic masses, for they are composed of grains of quartz, feldspar, and hornblende or augite. . . . . The great thickness of the sediments shows that the area was one of deposition for a considerable time, though the general coarseness of the material shows that the deposition was relatively rapid, and took place on a coast-line. Presumably the coast-line fringed a large continental area, from the surface of which rivers carried large quantities of sand.[1]

Preservation of the grains of decomposable minerals, however, cannot safely be taken as certain proof of topset origin of the beds in which they occur, for it is conceivable that, with a very abundant supply of terrigenous material during a period of little or no subsidence, similar material might be buried in foreset beds.

Barrell[2] has indicated the origin of alternations of sandy and muddy layers of small thickness as a result of topset deposition. The sediment on the outer, deeper part of the continental shelf, near the maximum depth at which the bottom is ever stirred by wave action, is affected only by the waves produced by exceptionally severe storms, such as occur only once in a number of years. During the interval between two such storms an unsorted mixture of mud and fine sand accumulates. When a storm occurs, the gentle stirring of the bottom which it produces causes the finer particles of the superficial layer to go temporarily into suspension, the larger grains remaining as a layer of clean washed sand. After the storm, subsidence being continually in progress, another layer of sandy mud is laid down above the sand, and by the time the next great storm occurs the sand layer and the deeper part of the

[1] P. Marshall, *Geology of New Zealand* (Wellington: Government Printer, 1912), pp. 184–85.

[2] J. Barrell, "Criteria for the Recognition of Ancient Delta Deposits," *Bull. Geol. Soc. Am.*, XXIII (1912), 428.

overlying mud layer have been so deeply buried that they are secure from further disturbance. The sand of a superficial layer is, however, again washed clean, and so the process goes on until there are innumerable alternating sand and mud layers throughout a great thickness of strata.

Toward the outer part of the mass of sediment intercalations of foreset beds and pelagic deposits may be present in the topset beds owing to advances and retreats of the edge of the shelf corresponding to fluctuations in the ratio of waste supply to rate of subsidence, the possibility of which has been pointed out on an earlier page. In Fig. 7, which represents diagrammatically a section of a shelf

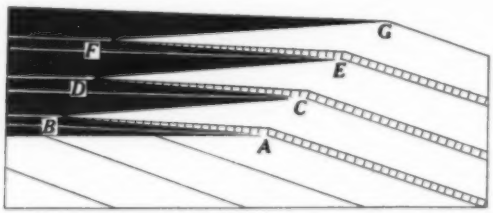

FIG. 7.—Alternation of lithological types in shelf deposits resulting from fluctuation in the ratio of supply of waste to rate of subsidence. Topset beds, black; foreset beds, white; pelagic beds, with cross-lines. The top of the shelf at successive stages is shown by the white lines. The vertical scale is exaggerated about ten times.

the front of which has alternately retreated and advanced during upward growth, *A* is the front of a shelf built forward during a period of stillstand preceding the subsidence, *B*, *D*, and *F* are positions of the front after episodes of small ratio of waste supply to rate of subsidence, and *C*, *E*, and *G* are positions of the front after episodes during which this ratio has had a large value. In order to simplify the diagram the lateral transitions from one type of sediment and from one slope to another are represented as perfectly sharp, but it must be borne in mind that in nature these transitions are gradual.

An inspection of this diagram makes it clear that above *A* there will be in the region represented by the middle part of the diagram the following succession:

10	Topset beds.....	Coarse- to fine-grained sandstone, arkose, and greywacke, with interbedded shale or argillite.
9	Foreset beds.....	More or less calcareous bluish mudstone or greensand.
8	Pelagic beds.....	Argillaceous to pure limestone, perhaps glauconitic, or somewhat sandy.
7	Topset beds.....	As above.
6	Foreset beds.....	As above.
5	Pelagic beds.....	As above.
4	Topset beds.	
3	Foreset beds.	
2	Pelagic beds.	
1	Topset beds.	

Farther seaward there will be no intercalations of topset deposits, but an alternation of limestone bands with bluish mudstone,

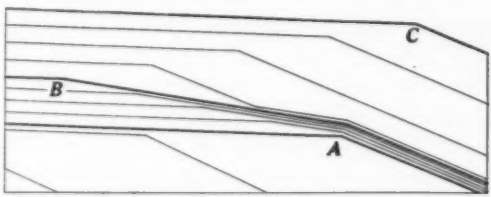

FIG. 8.—Enlargement of the portion *ABC* of Fig. 7

marl, or greensand. In this way may perhaps be explained the intercalation of the Amuri limestone of New Zealand, between mudstone and marl in Marlborough, and between greensand and glauconitic sandy limestone passing upward into marl in North Canterbury, and also the intercalation of the Oamaru limestone between beds of greensand in Otago, New Zealand.

The intercalations of foreset beds in the pelagic deposits will become more calcareous and thinner and will finally die out seaward. Obviously, under certain conditions of restricted waste supply this may occur in moderately shallow water, the proportion of foreset beds in the whole mass of sediment being very small.

In Fig. 7, which is designed to represent the vertical distribution of lithological types, the continuity of strata is not apparent, but in Fig. 8, which is an enlargement of the portion *ABC* of Fig. 7, the

continuity of strata is shown. It will be seen that in the section *AB*, built during the period of retreat of the shelf front from *A* to *B*, the topset beds will pass laterally into pelagic deposits, and that in the section *BC*, built during the period of advance from *B* to *C*, the first-formed strata will pass somewhat rapidly through foreset beds into pelagic deposits. In the later-formed strata of the section *BC*, however, the foreset portions will assume greater importance, the transition to pelagic deposits taking place in the deeper water farther seaward.

STRUCTURE OF A SHELF BUILT DURING NEGATIVE MOVEMENT

Negative movement generally involves uplift of the adjacent lands as well as of the sea floor. So erosion will as a rule be revived and the supply of waste increased. Also as the sea retreats the former surface of the shelf will be subject to subaërial and marine erosion, producing a further supply of waste. Negative movement will therefore be generally accompanied by heavy sedimentation on the continental slope.

It is conceivable, therefore, that the shelf may grow seaward with sufficient rapidity to maintain its edge at the usual depth throughout a period of rather rapid movement. During such movement the width of the shelf (measured from the ever-changing shore line) may diminish, remain constant, or even increase. In the first case the topset slope will be steepened by submarine erosion, and in the last case it will become less steep owing to deposition of topset beds. With constant width will go constant slope, with neither deposition nor erosion, the erosion that goes on at the shore line affecting only the emerging land.

From the foregoing it appears that, while topset beds are not necessarily absent, they can be only very thin, and they will be largely removed by erosion as the shelf emerges. The bulk of the deposit forms foreset beds, and the material of these will be of somewhat coarse texture.

THE NORTHWARD EXTENSION OF THE PHYSIOGRAPHIC DIVISIONS OF THE UNITED STATES

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PART I

INTRODUCTION

Preliminary to a study of the economic bearing of the physiography of North America the writer found it desirable to inquire into the extension of the generally recognized physiographic divisions of the United States southward into Mexico and northward into Canada and Alaska. The results of the study of Mexican physiography were published in the *Journal of Geology* early in 1916.[1] The present paper embodies the results of an investigation of the northward extent of these divisions.

The plan of this paper is to discuss briefly the physiographic divisions of the United States which touch our northern border, and to compare with them the adjacent territory north of the International Boundary by reference to surface features, boundaries, structure, and physiographic history, and by this means to show that the divisions of the United States have northern extensions that project them far into Canada and in some places into Alaska.

This paper is avowedly one of correlation, and no effort has been made to give detailed descriptions of the Canadian or Alaskan areas. Such work must be left to the future, as there are still large expanses of territory that have never been fully explored, much less studied, with care sufficient to allow an accurate classification of surface features or the drawing of permanent boundaries. The generalizations advanced in this paper will, of course, be subject to change as our knowledge of the north country increases.

Fenneman's classification has been used wherever it could be adapted to the continental scope of this paper. The writer's own

[1] W. N. Thayer, *Jour. Geol.*, XXIV (1916), 61–94.

experience and field study have contributed in a small way to the text, but he has also drawn liberally on the published work of others. He is particularly indebted to Dr. N. M. Fenneman for advice and criticism.

THE COAST RANGES SECTION OF THE PACIFIC BORDER PROVINCE

The term "Coast Ranges" may be used with perfect freedom when discussing topographic features within the United States, because in both popular and scientific thought the mountains designated by the term are quite definitely delimited. Freedom in the use of the term is restricted beyond the International Boundary, however, for in Canada there is also a "Coast Range" in no way related to the "Coast Ranges" of the United States, and the name is very definitely fixed in the language of the people as well as in scientific usage. It becomes necessary, therefore, to distinguish these features by appropriate terms that shall leave no room for ambiguity. This will be done in the present paper by the expedient of using the plural form, "Coast Ranges," for those mountains both in the United States and in Canada which face the open ocean and the singular form, "Coast Range," for that Canadian member of the Pacific System which is separated from the open ocean by numerous mountainous coastal islands. The two features have but little in common and differ widely in their records of physiographic history.

The mountains that border the coast of the United States from the Sierra de Los Angeles to the straits of San Juan de Fuca "are neither a single range nor alike in character and history, but they are for the most part contiguous and may be treated as a single general province."[1] A similar characterization may be made of the mountains of Vancouver and Queen Charlotte islands, the Alexander Archipelago, the St. Elias group, the Kenai Peninsula, and Kodiak Island, and for the same reasons they may be considered as an extension of the Coast Ranges of the United States and as belonging to the same province.

There is some objection to this broad view, particularly because a large part of the region north of the forty-ninth parallel has not

[1] N. M. Fenneman, *Ann. Assoc. Am. Geog.*, IV, 133.

been studied in detail, but it is supported in a general way by numerous geologists who have studied portions of the northwest coast of North America. Dawson,[1] Ransome,[2] and Clapp[3] tentatively place the mountains of Vancouver and Queen Charlotte islands in the province with the Coast Ranges, and Willis and Smith[4] are definitely committed to the idea. Bancroft[5] says that the system of the Coast Ranges is continued northward along the coast of Alaska in the mountainous islands of the Alexander Archipelago, and that these islands express the probable continuity of a range that formerly bridged all gaps existing between the Olympic Mountains of Washington and the St. Elias group of Alaska. Brooks[6] continues the system northward, connecting the Alexander Archipelago with the St. Elias group and that group, through the Chugach Mountains, with the mountains of the Kenai Peninsula and Kodiak Island.

The four more or less dissimilar divisions of the Coast Ranges in the United States have this in common—they represent dissected peneplains. Topographically they consist of individual ridges, and, excepting the Klamath Mountains, they follow the contour of the coast with considerable parallelism between them. The tops of the ridges are generally flat and the upland has a rolling, mature character, with peaks rising here and there above the general level. These peaks are residuals or monadnocks that resisted erosion during the first cycle. Diastrophism and vulcanism have contributed something to the present topography, but, though locally prominent factors, they have been generally subordinate to erosion.

The drainage of the Coast Ranges is a reliable index to the causes that have produced the present topography. The larger westward-flowing streams, that is, those which cut across the ranges to empty their waters directly into the Pacific, are without exception antecedent. They have preserved the courses which they

[1] G. M. Dawson, *Bull. Geol. Soc. Am.*, XII, 61.

[2] F. L. Ransome in *Problems of American Geology* (Yale University Press), p. 359.

[3] C. H. Clapp, *Geol. Survey Canada, Guide Book No. 8*, Part III, p. 280.

[4] Bailey Willis and G. O. Smith, *U.S. Geol. Survey*, Folio 54.

[5] J. A. Bancroft, *Geol. Survey Canada, Mem. 23*, p. 18.

[6] A. H. Brooks, *U.S. Geol. Survey, Prof. Paper 45*, pp. 27–42.

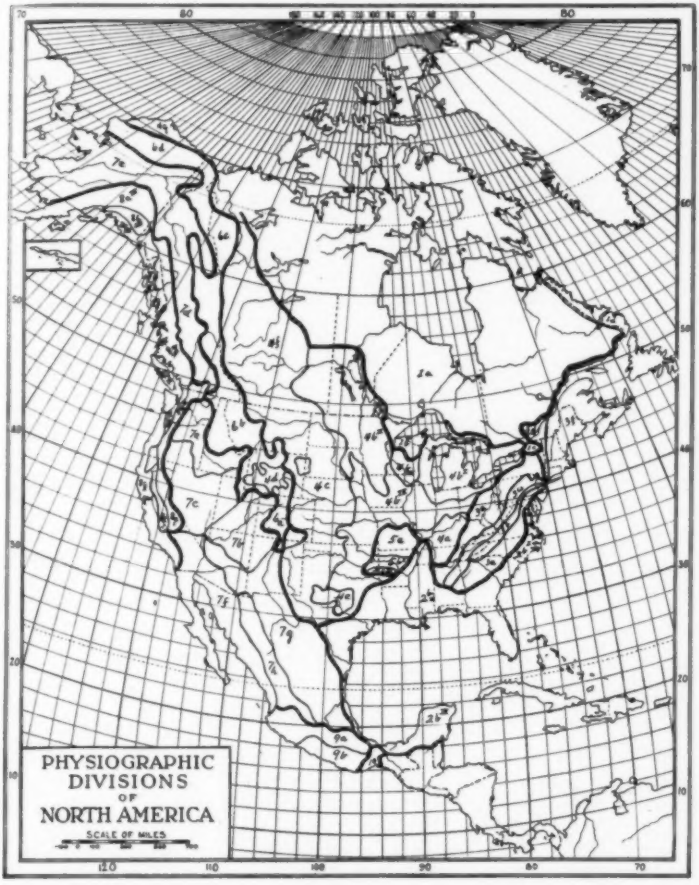
formerly had while the old surface was being subdued. The Sacramento and Columbia rivers are prominent examples of this type.

TABLE TO EXPLAIN THE ACCOMPANYING MAP

Major divisions, the strongly characterized parts of the continent, are separated by *heavy* lines, and are distinguished by Arabic numerals; *Provinces* are separated by *light* lines, and are distinguished by letters; *sections* are distinguished by Roman numerals.

Major Divisions	Province	Section
1. Laurentian Plateau	(*a*) Laurentian Plateau proper (*b*) Superior Highlands (*c*) Adirondack Mountains (*d*) Unnamed	
2. Atlantic Plain	(*a*) Continental shelf	
	(*b*) Coastal Plain	I. Atlantic section II. Gulf section III. Yucatan section
3. Appalachian Highlands	(*a*) Piedmont region (*b*) Blue Ridge Mountains (*c*) Appalachian Valley (*d*) St. Lawrence Valley (*e*) Appalachian Plateaus (*f*) New England region	
4. Interior Plains	(*a*) Interior Low Plateaus	
	(*b*) Central Lowland	I. East. Lake section II. West. Lake section III. Driftless area IV. Till plains
	(*c*) Great Plains (*d*) Wyoming Basin (*e*) Texas Hill region (*f*) Canadian Great Plains (*g*) Anatuvuk Plateau	
5. Interior Highlands	(*a*) Ozark Plateau (*b*) Ouachita region	I. Arkansas Valley II. Ouachita Mountains
6. Rocky Mountain System	(*a*) Southern Rockies (*b*) Boundary group (*c*) Mackenzie Mountains (*d*) Endicott Mountains	
7. Intermontane Plateaus	(*a*) Columbia Plateau (*b*) Colorado Plateau (*c*) Basin-and-Range province (*d*) Interior Plateaus (*e*) Yukon Plateau (*f*) Sonoran Desert (*g*) Anahuac Desert Plateau (*h*) Sierra Madre	
8. Pacific Mountain System	(*a*) Pacific Mountains	I. Sierra Nevada II. Cascade Mountains III. Coast Range of British Columbia IV. Coast Range of Alaska
	(*b*) Pacific Border province	I. California trough II. Puget trough III. Copper River basin
	(*c*) Coast Ranges	I. California-Oregon-WashingtonRanges III. Alaskan Ranges
9. Southern Mexican Highlands	(*a*) Volcanic province (*b*) Sierra del Sur province	
10. Isthmian Lowlands	(*a*) Tehuantepecan province	

The streams now occupying the longitudinal valleys have in part inherited courses from the earlier cycle, but they generally follow structural lines or have had their courses determined by folding



since the period of peneplanation (as in the Olympic Mountains), and are therefore subsequent.

In certain places, particularly in northern California, this section includes, besides the mountains proper, a tract of dissected

plateau immediately adjacent to the coast. This tract was eroded to the condition of a peneplain and later uplifted and dissected into its present form.[1] Local subsidences following the uplift drowned the lower courses of certain master-valleys, notably those of the Sacramento and Columbia rivers.

Although a large part of the Canadian division of the Coast Ranges has not been studied or mapped, a survey of the literature and maps available shows how similar are its topographic features to those in the United States. The topography of this division also represents a dissected peneplain, with residuals rising above the general level.[2] This region was extensively glaciated during the Pleistocene epoch, and many topographic features were developed which are not found farther south, such as smoothed and rounded mountains, scoured and terraced valleys, fiords, and superposed streams. However, when large areas are considered the topographic features appear to be analogous to those of the United States. A noteworthy similar feature is the coastal peneplain developed along the western margin of Vancouver Island. Associated with this are also wave-cut terraces, such as characterize the coastal peneplain in the United States, and in places a very irregular coast line due to later depression.

It is difficult to compare the topography of the Alaskan division of the Coast Ranges with that of the United States on account of the pronounced effect of Pleistocene and Recent glaciation, particularly in the mountains of the Alexander Archipelago and the St. Elias Range. However, two conditions necessary to link this division to the remainder of the Coast Ranges have been definitely established. The mountains of Kodiak Island and the Kenai Peninsula present an upland surface which can scarcely be interpreted as other than the remnants of an ancient peneplain,[3] and there is abundant evidence of instability dating from early Tertiary to the present time. Another correlating feature may be found in the course of Alsek River across the St. Elias Range. This is probably an antecedent stream course, analogous to those of the Columbia and Sacramento rivers. The course of Copper River

[1] A. C. Lawson, *Univ. Cal. Bull.*, I, 242–44.

[2] C. H. Clapp, *op. cit.*, pp. 282–84.

[3] A. H. Brooks, *op. cit.*, p. 272.

across the Chugach Mountains may also fall within this classification.

The physiographic history of the Coast Ranges in the United States begins with the general uplift in the Pliocene period that started the erosion cycle which produced the first peneplain. During this cycle the master-streams outlined their present courses. The date of the uplift that began the present erosion cycle has not been definitely determined, but it may be assigned tentatively to late Pliocene time. The present topography, excepting residual peaks, and all tributary stream courses are the results of dissection during this later cycle.

North of the International Boundary there are records of a corresponding sequence of events. Diastrophism on a large scale was the dominant process during the Tertiary period until the close of the Miocene epoch. Erosion following an uplift, probably in Pliocene time, subdued the mountains of Vancouver and Queen Charlotte islands[1] and also the mountains of Kodiak Island and the Kenai Peninsula,[2] and it may fairly be assumed that it included the intermediate members of the Coast Ranges.

THE PACIFIC TROUGH SECTION OF THE PACIFIC BORDER PROVINCE

The great depression of the western coast of North America, known as the Pacific Trough, is a structural feature that extends, with minor interruptions, from Cape Corrientes, Mexico, northward to Alaska. It is made up of six natural divisions: the first and southernmost is the Gulf of California; the lowlands of the Lower Colorado Basin constitute the second; and the third is the Great Valley of California. The fourth comprises the Willamette and Cowlitz valleys and Puget Sound. The fifth or Canadian division extends northward from the Straits of San Juan de Fuca and includes the Straits of Georgia, Queen Charlotte Sound, and probably Hecate Straits. The sixth or Alaskan division extends apparently through Clarence and Chatham straits to Lynn Canal. The mountains of the St. Elias group interrupt the extension of the trough northward from Lynn Canal in very much the same manner as do the Klamath Mountains of the United States, but it is

[1] G. M. Dawson, *op. cit.*, p. 90. [2] A. H. Brooks, *op. cit.*, pp. 292, 293.

probably continued beyond them through the Copper River Basin, Sushitna Basin and Cook Inlet, and possibly includes the Shelikof Straits.

The divisions represented by the Lower Colorado Basin, the Great Valley of California, the Willamette and Cowlitz valleys, the Copper River Basin, and the Sushitna Basin are land surfaces; the remaining divisions are at present submerged. Within the United States the eastern and western boundaries of the subaërial divisions may be definitely drawn. The floor of the Great Valley is, for example, practically coextensive with the area of Quaternary deposits shown on geologic maps, and in Oregon and Washington the greater part of the depression is filled with glacial or fluvio-glacial deposits and alluvium formed during or since the glacial period. Brooks[1] uses the same criterion to delimit the terrane of the Copper River Basin, which he describes as a broad floor of Pleistocene gravel and silt deposits extending from the inland slope of the Chugach Mountains to the foothills of the Alaska Range. The boundaries of the submerged divisions may be regarded as practically coincident with the limiting shore lines.

The topography of the subaërial divisions within the United States may be characterized as a "floor." The broad, sloping alluvial plains of these sections are generally featureless. The slope of the valley floor generally increases toward the foothills, finally merging with the alluvial fans in the foothill gulches. In some places this merging is so gradual that it is impossible to say where plain ends and foothills begin. Brooks has applied the term "floor" to the Alaskan section and emphasizes its monotonous lack of relief.

"The Pacific Coast downfold has been a feature of the western coast since the Cretaceous period, and during several geologic periods was so deeply depressed as to lie beneath sea-level and receive a considerable body of sediments."[2] These marine sediments, however important geologically, do not contribute in any way to the present topography. The physiographer is concerned chiefly with the origin of the later alluvium and gravel deposits, which were produced by stream action after certain parts of the trough had been cut off from the sea. These deposits were of

[1] A. H. Brooks, *op. cit.*, p. 54. [2] Isaiah Bowman, *Forest Physiography*, p. 177.

course derived from the adjacent highlands, both to the east and west, and therefore the history of the growth and dissection of the mountains is in a large measure the history of the filling of the trough.

The mountainous province which borders the trough on the east has been contributing deposits since Cretaceous time. The Coast Ranges were probably sufficiently elevated in early Pliocene time to commence contributing to the filling of the trough. In late Pliocene time both mountain systems were further uplifted, increasing the carrying power of the streams and resulting in a more rapid filling of the depression. By the close of the Pleistocene epoch the deposits had accumulated to such a depth in certain places as to fill the trough to sea-level and to cut off parts of it from the sea. From that time to the present the history of the subaërial divisions has been that of flood-plain formation.[1] These facts apply chiefly to the divisions within the United States, but the deposits of the Copper River basin also bear evidence of a similar sequence of events in that division.[2]

The history of the submerged parts of the trough is important only as it contributes to the discussion of the land surface. The history of the Gulf of California has been recounted in the writer's paper on Mexico previously cited,[3] and Willis and Smith[4] have given a good summary of the history of Puget Sound. A review of the literature on the subject would lead one to believe that an identical series of events took place within the submerged parts of the trough in Canada and Alaska. From the data available at this time, however, it is impossible to make a positive statement.

THE SIERRA-CASCADE PROVINCE OF THE PACIFIC MOUNTAIN SYSTEM

This province comprises a very persistent mountainous feature of Western North America in which folding came to a close in Mesozoic time and which has since been comparatively rigid.[5] The

[1] F. L. Ransome, *Univ. Cal. Bull.* (Dept. Geol.), I, 387.

[2] A. H. Brooks, *op. cit.*, p. 54; also W. C. Mendenhal, *U.S. Geol. Survey, Prof. Paper 41*, p. 84.

[3] W. N. Thayer, *op. cit.*

[4] Bailey Willis and G. O. Smith, *op. cit.*

[5] F. L. Ransome in *Problems of American Geology*, pp. 358, 359.

various members of the mountain system are bound together in one great structure by a chain of batholiths, the intrusion of which seems to have begun in the north and continued progressively southward during a long period of time.[1]

The members of this mountain system in the United States are the Sierra Nevada, the Klamath Mountains, and the Cascade Mountains. To these might be added the Blue Mountains of Oregon. The Northern Cascade Mountains are generally regarded as ending at the International Boundary, but as a matter of fact they terminate naturally a few miles beyond the boundary at the canyon of Fraser River. Daly[2] has selected this as a dividing line, according to his plan of limiting physiographic units by master-valleys and trenches.

This province includes a section in Canada known as the Coast Range of British Columbia—a mountainous belt about 100 miles wide which extends along the coast for nearly 900 miles from the canyon of Fraser River northwestward beyond the head of Lynn Canal. Dawson[3] early objected to admitting the Coast Range to the same classification as the Cascades because of the decided difference in rock composition. Physiography, however, gives preference to structure and topography as criteria for classification, and, as Daly[4] has pointed out, "it has become more and more evident as the study of the Cordillera progresses that rock composition can never rival crest continuity as a primary principle in grouping the western mountains."

At its northern end the Coast Range passes behind the St. Elias Range and gradually blends with the Interior Plateaus near Lake Kluane.[5] Although this particular member terminates here, the province, following the trend of the other Cordilleran divisions, continues along a great arc to the northwest and embraces an Alaskan section of several members—in succession the Chigmit Mountains, the Alaskan Range, and the Aleutian Range.[6] In all

[1] A. C. Lawson, *Jour. Geol.*, I, 579–86.

[2] R. A. Daly, *Geol. Survey Canada, Mem. 38*, Part I, p. 41.

[3] G. M. Dawson, *Trans. Royal Soc. Can.*, sec. 4, p. 4.

[4] R. A. Daly, *op. cit.*, p. 40.

[5] J. A. Bancroft, *Geol. Survey Canada, Mem. 23*, p. 13.

[6] A. H. Brooks, *op. cit.*, pl. 7.

probability the system also includes the volcanic Aleutian Islands. In the absence of adequate data on the mountains of Alaska it should be remembered that any classification is merely tentative and is subject to revision as knowledge of the country becomes more thorough. However, there is considerable evidence to support the present classification. This will be given in the discussion of the topography and physiographic history of the region.

In a general way the topography of this province, particularly Sierra Nevada and Cascade mountains, is that of an uplifted (Tertiary) peneplain, which has been deformed by folding and faulting, deeply dissected by erosion, and covered deeply in places with volcanic products.[1]

The Sierra Nevada is a bold, continuous, and deeply dissected range, about 75 miles wide, with a crest line of well-defined residual peaks. The mountains are delimited on the east for hundreds of miles by a high and steep fault-scarp, but descend gradually to the Great Valley on the west across a gently sloping plateau.

The Cascade Mountains have also, in most places, a broad, maturely dissected summit of about the same width as that of the Sierras, above which rises a straight north-south line of several scores of volcanic peaks. Long, broad, flat-topped spurs, analogous in some respects to the crest of the High Sierras, diverge from these peaks. The eastern slope of the Southern Cascades is bold and the western slope gentle. In these respects also they resemble the Sierras. In the Northern Cascades, however, the eastern slope loses its abruptness and the peneplain of the mountains descends gradually to the plateau of the Columbia River.

Three types of volcanic products have contributed to the making of the present topography of the Sierra Nevada and Cascade mountains: (1) batholithic granite and diorite intrusives, (2) flows of basaltic lava, and (3) andesitic cones which rise above the general level and dominate the view from many points.

The drainage of these sections of the province is characteristic of its type of topography. The courses of the forks of Feather River across the crest of the Sierra Nevada, the course of the

[1] J. S. Diller, *U.S. Geol. Survey, Bull. 353*, p. 9; also I. C. Russell, *U.S. Geol. Survey, 20th Ann. Rept.*, Part II, p. 140.

Columbia River across the Cascade Mountains, and that of the Skagit River across the Skagit Mountains were outlined upon the surface of a Tertiary peneplain and have been maintained in spite of uplift to the present time. Most of the smaller streams are subsequent and have had their courses determined by structure or the relative hardness of rocks. Many of these latter have also had their courses altered by lava flows.

The Coast Range of British Columbia has a structure analogous to that of the Sierra Nevada and Cascade mountains,[1] and its topography is strikingly similar. These mountains are also the remnants of an uplifted and dissected (Tertiary) peneplain, the relief of which has been increased by later "warping, flexure, or displacement."[2] They are from 60 to 100 miles in width and of fairly uniform height. Many residual peaks rise along the crest line to a considerable elevation above the general level. Where erosion has removed the overlying sedimentary rocks a number of great batholiths are exposed, which may be regarded as connecting the Coast Range structurally with the southern members of the system. The eastern slope of the mountains is very gentle, as in the Northern Cascades, and in many places it merges insensibly with the Interior Plateaus.[3]

The principal rivers which flow across the Coast Range from the interior are antecedent to the uplift, and have maintained to the present time courses which they originally established on peneplaned surface that sloped westward to the ocean. Chief among these are the Fraser, Stikine, and Taku.[4]

It is difficult to give a clear summary statement of the topography of the Alaskan section on account of the small amount of geological work and mapping that has been done. Suffice it to say, however, that the Chigmit and Alaska ranges are bold, mountainous features, and the available evidence indicates that they have been carved from a Tertiary peneplain after differential uplift.

[1] A. C. Spencer, *U.S. Geol. Survey, Bull. 287*, pp. 10, 11; also G. O. Smith, *U.S. Geol. Survey*, Folio 86.

[2] A. C. Spencer, *Bull. Geol. Soc. Am.*, XIV, 117–32.

[3] R. G. McConnell, *Geol. Survey Canada, Guide Book No. 10*, pp. 7–11.

[4] A. H. Brooks, *op. cit.*, p. 271.

This fact has not been fully established, however, and since there is apparently no accordance of summit levels, the origin of these mountains may still be open to question. The Aleutian Range with its long line of typical cones built along an anticlinal axis closely resembles the Cascades. As a matter of correlation it may be remarked that intermittent vulcanism has continued in both sections to the present time.[1]

The physiographic history of this province properly begins with the emergence of the area from the sea at or near the close of the Mesozoic era. Deformation either accompanied the emergence or closely followed it, and then from a point as far north as the sixtieth parallel to the southern end of the Sierra Nevada folding on a large scale came to a close. Since Cretaceous time the system has been comparatively rigid, and its various units in so far as they have moved at all have moved *en masse* or in large fault-blocks.[2]

The present mountains, however, were not produced by deformation only. Several forces have worked together from the close of the Mesozoic era to the present time to produce the topography as we now see it. This will be shown in a brief summary sketch of the history of the various units.

In the Sierra Nevada the present simple orographic form is strikingly contrasted with an older and quite complex structure which was developed during the Mesozoic deformation, and which consisted of strong folds intruded by extensive granodiorite batholiths. In late Cretaceous time these folds were truncated by erosion and the surface reduced to one of low relief.[3] The Eocene epoch was probably a time of mild deformation and uplift. This began an erosion cycle that culminated in the Miocene epoch by reducing the area to a peneplain.[4] Another uplift late in the Pliocene epoch raised this peneplain to the level of the plateau, now dissected, which lies between the crest of the Sierras and the Great Valley. The crest of the Sierras, or, as it is frequently called, the High Sierras, stands several thousand feet above the general level

[1] A. H. Brooks, *op. cit.*, p. 275.

[2] F. L. Ransome, in *Problems of American Geology*, pp. 358, 359.

[3] F. L. Ransome, *op. cit.*, p. 351.

[4] J. S. Diller, *U.S. Geol. Survey, 14th Ann. Rept.*, Part II, pp. 404–11.

and is not a part of the Miocene peneplain. It is the residual part of the surface that was reduced in late Mesozoic time.[1]

A similar record of events is preserved in the Cascade Mountains. A range corresponding to the present Cascades was probably formed by folding during the Mesozoic era accompanied by intrusions of igneous rock, but the configuration of the present range is ascribed to later events and processes. In early Tertiary time the region was comparatively rugged. During the earlier epochs of the Tertiary period there was an alternation of basaltic lava flows and shallow water deposition. The Miocene epoch was a time of further mild deformation, followed by an erosion interval that subdued the whole region. This subdued surface was uplifted during the Pliocene epoch to form the mass of the present Cascade Range.[2] Erosion and vulcanism have since combined to produce the present topography from this uplifted peneplain.

On a previous page an attempt was made to justify the classification of the Coast Range of British Columbia with the Sierras and Cascades on a basis of crest-continuity. A further justification is found in the record of the physiographic history of the Coast Range. The later part of the Mesozoic era was in this region also a time of deformation and granitoid batholithic intrusion. Erosion followed this deformation and produced a peneplain, or at least a subdued surface. Milder deformation, probably in the Miocene epoch,[3] uplifted this subdued surface, and another erosion cycle was started, which before the close of the Pliocene epoch had produced a second peneplain. Late Pliocene time witnessed another uplift and the beginning of the erosion cycle that produced the topography as it now appears.

Writers do not all agree regarding the Tertiary peneplains of the Cascades and the Coast Range of British Columbia, the existence of which is inferred from the accordance of summit levels. Russell[4] and Willis and Smith[5] agree on a late Tertiary base level

[1] Isaiah Bowman, *op. cit.*, p. 170.

[2] G. O. Smith, *U.S. Geol. Survey*, Folio 86.

[3] A. C. Spencer, *Bull. Geol. Soc. Am.*, XIV, 117–32.

[4] I. C. Russell, *U.S. Geol. Survey, 20th Ann. Rept.*, Part II, pp. 140–44.

[5] Bailey Willis and G. O. Smith, *U.S. Geol. Survey, Prof. Paper 19*.

produced according to the peneplain theory of Davis. Daly[1] opposes this idea, however, in so far as it applies to the region under discussion, and explains the accordance of summit levels on a different principle. Without attempting to pass upon the relative merits of the theories, it may be remarked that the general topographic features are at least consistent with the peneplain hypothesis.

The sequence of physiographic events in the Alaskan section is difficult to determine. A probable summary is as follows: first, crustal disturbance in the late Mesozoic era and the opening of numerous volcanic vents at about the same time; second, peneplanation toward the close of the Tertiary period; and third, later differential uplift and erosion that in a large measure contributed to the present topography.[2] Though this statement should be accepted as subject to revision as our knowledge of Alaskan geography and geology increases, it appears probable that the major events of physiographic history in Alaska have followed the schedule described for the remainder of the province.

THE INTERMONTANE PLATEAUS

East of the mountains of the Pacific System lies a broad belt of country which, though characterized in many places by mountains and valleys or basins, presents on the whole a plateau surface, in part degraded, in part constructional. This belt of plateaus extends from Mexico northward to the Bering Sea and includes the Great Basin, Colorado and Columbia plateaus of the United States, the Interior Plateaus of British Columbia, and the Yukon Plateau of Alaska. It is bounded throughout its entire extent on the east by the Rocky Mountains.

Although there is some diversity of surface features among the several units of this intermontane belt, particularly between widely separated units, there is sufficient similarity among them in the relation of each to the adjoining provinces on the east and west, in their principal structural features, and in their records of

[1] R. A. Daly, *Geol. Survey Canada, Mem. 38*, pp. 631–41.

[2] A. H. Brooks, *op. cit.*, pp. 290–95.

physiographic history, to enable us to classify them as closely related provinces of a single major division.

Topographically the Great Basin is a region of fault-block mountains and detritus-filled valleys or basins, with small areas of horizontal lava flows scattered over its surface. Its altitude is everywhere lower than that of the bordering provinces. Ransome says that "the impressive feature of the Great Basin . . . . to one . . . . who looks over it from the crest of the Sierras or from the edge of the Colorado plateaus in Arizona is that it is a collapsed region."[1] The western boundary is characterized throughout almost its entire length by a fault-scarp that rises sharply to the crest of the Sierras. The eastern boundary is in some places a prominent scarp and in others a gentle slope from the adjacent highlands.

The Columbia Plateau, although built of almost horizontal lava flows and lacking on the whole the detrital filling of the Great Basin, is not to be sharply separated from it. Fenneman[2] shows a broad transition zone between the two divisions. This province, like the Great Basin, also lies between and beneath two mountain provinces.

Prior to the extrusion of the lavas which now form its surface the Columbia Plateau was a region of rugged topography,[3] probably not unlike the Great Basin before the beginning of the period of basin-filling. This rugged surface was not entirely obscured by the lavas, as witness the Blue Mountains of Oregon. There is some evidence that there may have been a fault-scarp separating the plateau from the Cascades, but if such was the case it has been obscured by the lavas, and today the eastern margin of the peneplain of the Cascades descends gradually to the plateau of the Columbia apparently without a break.

The similarity between the Columbia Plateau and the Interior Plateaus of British Columbia is striking, although the two provinces are not contiguous, being separated a distance of something less than 100 miles by the Colville Mountains, which stand like a bridge across the plateaus and connect the Rockies with the Cascades.

[1] F. L. Ransome, *op. cit.*, p. 343. [2] N. M. Fenneman, *op. cit.*, pl. 2.

[3] I. C. Russell, *U.S. Geol. Survey, Bull. 199*, p. 61.

A large area of the Interior Plateaus is covered by basaltic lava flows of the same age as those of the Columbia Plateau, and where these are favorably disposed for observation it may be seen that they obscure a former rugged relief.[1] The present topography is conditioned, however, by factors other than lava flows and anterior relief. It represents in part dissected lava tables, in part dissected local peneplains of pre-Miocene age, and in part dissected mountain torsos reduced during early Tertiary and Mesozoic times.[2] In general, the topography may be described as a series of gently undulating and plateau-like uplands, from 4,000 to 6,000 feet in altitude, within which the streams have cut wide and deep valleys.

A significant feature of the Interior Plateaus, in fact, of the entire belt of Intermontane Plateaus, except the Great Basin, is the antecedent drainage. The basalt cover of the plateaus, originally horizontal, was later deformed, but the deformation was not rapid enough to affect seriously the streams that had been laid out on nearly flat lava sheets in response to initial slopes, and which have maintained their courses to the present day. Where there have been great uplifts we now find deep canyons. The Columbia River where it crosses the province is typical of this condition, as are also the Fraser, Skeena, Nano, Stikine, and Taku rivers.[3]

The Interior Plateaus lie below two adjacent and limiting provinces and are similar in this respect to the Columbia Plateau and the Great Basin. The eastern boundary is not marked by a prominent topographic break at any place, but a difference of surface features may be easily distinguished within a few miles. On the west, where the Interior Plateaus are bordered by the Coast Range, the boundary of the province is difficult to determine. The mountains and plateaus merge insensibly in many places[4] and present a case analogous to that of the Cascades and the Columbia Plateau in Washington.

The Interior Plateaus of British Columbia are continued northward into Yukon Territory and Alaska under the name of Yukon

[1] L. Reinecke, *Geol. Survey Canada, Mus. Bull. 11*, Fig. 1 and p. 38.

[2] R. A. Daly, *Geol. Survey Canada, Guide Book No. 8*, Part II, p. 164.

[3] A. C. Spencer, *Bull. Geol. Soc. Am.*, XIV, 125–28.

[4] R. G. McConnell, *Geol. Survey Canada, Guide Book No. 10*, p. 11.

Plateau. There is no natural dividing line between these two units, and any line that is drawn to separate them must be arbitrary. No dividing line is necessary except for convenience in discussion, and for this purpose the political boundary between British Columbia and Yukon Territory is as satisfactory as any other, particularly as it practically coincides with the watershed that separates the headwaters of the Yukon River from the rivers flowing southward.

Topographically this division is a dissected plateau. The summits are accordant on the whole, though here and there isolated residuary masses rise above the general level.[1] Structurally the area has the form of a "broad shallow trough pitching to the north, whose axis coinciding with the valley of the Yukon trends northwest to the Arctic circle and then bends to the southwest. In other words, the trough makes nearly a right-angled bend and pitches toward Bering Sea."[2]

The Yukon Plateau has an altitude of 4,000 to 5,000 feet where it is bordered by the Coast Range, falling near the center to about 3,000 feet, and rising again as it approaches the Rockies. Along a part of the southwest margin the plateau abuts almost directly against the slopes of high mountain ranges, and so abrupt is this change from the smooth, flat summits of the upland to the rugged mountains that it is very suggestive of a fault-scarp.

It is apparent that the Yukon Plateau may be correlated with the other members of the Intermontane Plateaus, not only because of general similarity of surface features, but also because it lies between two mountain provinces. The probable fault-scarp along the western border suggests an analogy to that between the Great Basin and the Sierra Nevada. In fact, Brooks states specifically that the "Yukon Plateau is coextensive (continuous) with the plateau of British Columbia and can be regarded as belonging to the same physiographic province as the Great Basin."[3]

Along the remainder of the western border, however, the relation between plateau and mountains is more like that existing between the Coast Range and the Interior Plateaus or between the Cascades and the Columbia Plateau. This is particularly true

[1] F. E. Wright, *Geol. Survey Canada, Guide Book No. 10*, pp. 53, 54.

[2] A. H. Brooks, *op. cit.*, p. 278. [3] A. H. Brooks, *op. cit.*, p. 41.

in the region adjacent to White and Chilkoot passes, and in the vicinity of White and Stikine rivers. In these places the summit plateau of the mountains blends with the plateau of the interior.[1]

The physiographic history of the Intermontane Plateaus is coincident with that of the mountain provinces bordering them on the west down to Eocene time,[2] and since the latter has been discussed in preceding pages it will not be necessary to repeat it here. The Eocene epoch witnessed widespread volcanic action of great magnitude in the Columbia Plateau division, and lesser, localized action in the northern divisions, accompanied by an uplift of the previously subdued surface. An erosion interval followed in the Oligocene epoch. Whatever effect it may have had on the Columbia Plateau is now largely obscured. Drysdale[3] records a post-Eocene–pre-Miocene erosion interval for the Interior Plateaus and Brooks[4] records a post-Eocene erosion interval for the Yukon Plateau. Dawson,[5] Spurr,[6] Spencer,[7] and others have correlated the peneplains thus produced as belonging to the same period, making it appear that between the close of the Eocene epoch and the beginning of the Miocene epoch there was a period of widespread peneplanation. Daly,[8] however, insists that there was no period of general peneplanation, and states that the upland surface was produced by several pre-Miocene erosion cycles. The residual mountains of British Columbia, Yukon Territory and Alaska, and the Blue Mountains of Oregon probably represent masses which remained unsubdued during this time (one or more cycles as the case may be), although they may date back to the early Tertiary or late Mesozoic erosion period.

The first basaltic flows on the Columbia Plateau are assigned to the Miocene epoch.[9] Similar flows, more localized, however,

[1] A. C. Spencer, *op. cit.*, pp. 125–28.

[2] G. O. Smith and F. C. Calkins, *U.S. Geol. Survey, Bull. 235*, pp. 85–90.

[3] C. W. Drysdale, *Geol. Survey Canada, Guide Book No. 8*, Part II, pp. 235, 236.

[4] A. H. Brooks, *op. cit.*, pp. 278, 279.

[5] G. M. Dawson, *Trans. Royal Soc. Can.*, VIII, sec. 4, p. 12.

[6] J. E. Spurr, *U.S. Geol. Survey, 18th Ann. Rept.*, Part III, p. 260.

[7] A. C. Spencer, *op. cit.*, p. 128.

[8] R. A. Daly, *Geol. Survey Canada, Guide Book No. 8*, Part II, p. 164.

[9] I. C. Russell, *op. cit.*, p. 61.

occurred at the same time on the Interior Plateaus and on the Yukon Plateau.[1]

Throughout all Tertiary time the belt of intermontane plateaus north of the Great Basin was fairly rigid.[2] However, in late Miocene time slight orogenic movements warped the early Miocene lavas into broad synclinal basins and anticlinal domes.[3] These movements were probably coincident with the profound faulting movements which affected the Great Basin. Lava flows which continued until very recent time have largely obscured the evidence of such movements on the Columbia Plateau, but they are plainly to be seen in the northern divisions.

Late in the Pliocene epoch there was a general but differential uplift of the entire Cordilleran region. This prepared for the development of the present upland surface. Dissection following this uplift marked out the main features of the present topography. The erosion cycle thus begun was halted, however, north of the Columbia Plateau by the formation of the Pleistocene ice cap. Normal processes of erosion which were renewed after the withdrawal of the ice have continued the dissection, but the topography bears the characteristic marks of glacial modification.

THE ROCKY MOUNTAIN SYSTEM

East of the Intermontane Plateaus and bordering this region throughout almost its entire length is another major division of general Alpine habit in strong topographic contrast with the plateaus. It is the most difficult of all the Cordilleran regions to name or define, because of the indefinite and varied manner in which names have been applied to it and its subdivisions.

A ruling of the United States Geographic Board makes the term "Rocky Mountain System" embrace the whole of the mountainous region between the forty-ninth parallel and the Rio Grande River. However, this definition does not harmonize with recent studies in physiographic boundaries, as it includes a large area in Texas and New Mexico of a character essentially different from that of the mountains, and excludes a large and closely related region north

[1] L. Reineke, *op. cit.*, p. 38.

[2] F. L. Ransome, *op. cit.*, p. 338. [3] C. W. Drysdale, *op. cit.*, pp. 235, 236.

of the forty-ninth parallel. Daly[1] limits the use of the term to what is really the Canadian extension of the Front Ranges of the United States and fails to recognize that the term "Rocky Mountains" is used in a very much broader sense by both popular and scientific writers in the United States. Ransome[2] applies the term "to the whole of that part of the Laramide System which extends from the Bering Sea to the southern ends of the San Juan and Sangre de Cristo ranges in Colorado." Fenneman[3] makes his Rocky Mountain division within the United States include practically the same area as Ransome's, though the latter wrote of general geology rather than physiography.

There is something to be said, of course, in favor of each of these definitions, as well as of the earlier nomenclature proposals of Dawson and Dana, more or less perhaps as one lives north or south of the forty-ninth parallel. However, in spite of all that may be written, and in the face of frequent inconsistencies, *popular usage* will always be the final arbiter in questions of geographic names, and as Ransome's and Fenneman's definition conforms more nearly to popular usage than the others it will be used in this paper.

The Canadian divisions of the Rocky Mountain System are easily correlated with the divisions lying within the United States; in fact, the so-called "Northern Rockies" of the United States and the ranges of British Columbia belong to one and the same province. This province may be further subdivided into four orographic units, separated among themselves and from adjacent provinces by five roughly parallel, structural, north-south lines, namely, (1) the western edge of the Great Plains; (2) the Rocky Mountain trench; (3) the Purcell trench; (4) the Selkirk valley; and (5) the eastern edge of the Intermontane Plateaus.[4]

The Rocky Mountain trench is a long, narrow, intermontane, structural depression or trough that extends from Flathead Lake in Montana northward almost to the boundary between British Columbia and Yukon Territory, a distance of about 990 miles.

[1] R. A. Daly, *Geol. Survey Canada, Mem. 38*, p. 27.

[2] F. L. Ransome, *Problems of American Geology*, p. 291.

[3] N. M. Fenneman, *op. cit.*, pp. 119–24 and pl. 2.

[4] R. A. Daly, *op. cit.*, p. 26.

It is occupied successively by the headwaters of the Columbia, Fraser, Peace, and Liard rivers, nearly all of which leave the trough by transverse gorges cut in the adjacent mountains.

The orographic unit lying between this trench and the western edge of the Great Plains includes the Lewis, Livingstone, Mission, and a few smaller ranges in the United States, and Daly's "Rocky Mountain System" of British Columbia and Alberta.[1] The topography of these ranges is generally bold, and elevations of more than 10,000 feet are attained by some of the peaks. These are the true *front ranges* of this part of the Rocky Mountain System.[2]

The Purcell trench is also a structural trough. It extends from Bonners Ferry, Idaho, northward in line with the courses of the Kootenay and Beaver rivers to a point about 200 miles north of the International Boundary, where it joins the Rocky Mountain trench.

The orographic unit that lies between these two trenches comprises the Coeur d'Alene, Cabinet, Flathead, and Purcell ranges. The relief is less than that of the Front Ranges. Few peaks surpass 7,500 feet, except in a part of the Cabinet Range, and on the whole only a small proportion of the summits attain 7,000 feet. The more important stream courses trend about northwest and form boundaries of the chief subdivisions, each of which bears evidence of being a dissected plateau.[3]

The Selkirk Valley, although not a structural depression, is a valley of the first rank. It is drained southward by the Columbia River, and extends from a point about 60 miles south of the International Boundary, where the river turns westward to enter the lava fields of the Columbia Plateau, to a point about 250 miles north of the boundary, where it also joins the Rocky Mountain trench.

The mountainous unit lying between the Selkirk Valley and the Purcell trench embraces Daly's Selkirk System, which in its extension south of the boundary includes the Pend d'Oreille Mountains. The topographic character of this unit is similar to that of the unit next to the east. In the southern part the mountains are generally rounded, and but few of the summits rise above 5,000 feet. North

[1] F. C. Calkins, *U.S. Geol. Survey, Bull. 384*, p. 12.

[2] Bailey Willis, *Bull. Geol. Soc. Am.*, XIII, pp. 305–52.

[3] F. C. Calkins, *loc. cit.*

of the boundary, however, they are more rugged, and in places peaks attain heights of 7,000 feet.[1]

The fourth orographic unit lies between the Selkirk Valley on the east and the edge of the Intermontane Plateaus on the west, excepting a distance of about 75 miles south of the International Boundary, where it abuts against the Cascade Mountains. It embraces Daly's Columbia System, which includes the Colville Mountains of Washington. This unit is characterized by comparatively low mountains that commonly show a certain uniformity of summit levels. Topographically they are not sharply distinguished from the mountains of the Interior Plateaus; however, there are no remnant plateaus, and they are to be regarded as a group distinct from any association with the mountains of that division.[2]

These four units form a group which writers on the physiography of the United States have frequently referred to as the "Northern Rockies." This term fails to convey a proper idea of their relative location on the continent, however, and in the absence of a better name, as well as for convenience in discussion, they will be referred to hereafter in this paper as the "Boundary Group."

Just north of the sixtieth parallel rise the Mackenzie Mountains, the greatest mountain group of Canada. This group consists of two ranges—an older range against the eastern edge of which a newer or front range has been built up. It has a crescentic axis, paralleling the general trend of the Cordilleran provinces, and extends from the valley of the Liard River to the valley of the Porcupine River. The group has a maximum width of about 300 miles. There is no well-defined crest line, and it appears to be a complex of mountain masses which are the result of deformation and erosion following an uplift.

The topography of the older western range is governed to some extent by structure, many of the wider valleys being cut in soft strata, and the higher ridges and peaks formed by uptilted hard beds. The highest peaks and most-rugged crests are built of granite stocks. The surface features in general are those which result from long-continued differential erosion acting on an uplifted and

[1] F. C. Calkins, *op. cit.*, p. 12.

[2] O. E. LeRoy, *Geol. Survey Canada, Mem. 21*, p. 23.

deformed region, somewhat modified by glaciation. Some of the higher peaks are estimated to measure 8,000 feet, but the general vertical relief is from 3,000 to 4,500 feet.

The eastern or newer range displays a marked difference in topography. Its structure is due to fracturing, buckling, and faulting, which has resulted in a more rugged and compact range of crumpled and tilted blocks. The highest peaks are roughly pyramid-shaped masses that reach elevations of 6,500 to 7,500 feet. Erosion has not reached such an advanced stage as in the western range.

Keele[1] regards the Mackenzie Mountains as closely related in both geology and structure to the Boundary Group, and, applying the various criteria used by physiographers, it would seem that this group may be definitely placed in the same classification as the Rocky Mountains.

Just beyond the boundary between Yukon Territory and Alaska another mountain group rises and extends westward toward Bering Sea. The name Endicott Mountains, originally applied to a single range of this group, is now made to include the whole.[2] Brooks[3] correlates these mountains as an orographic continuation of the Mackenzie group and as a part of the great physiographic division of the Rocky Mountain System.

The Endicott Mountains are sharply defined. They are bounded on the south by the Yukon Plateau and on the north by the Anatuvuk Plateau, a part of the Great Plains province. The southern slope rises rather abruptly from the uplands of the Yukon Plateau, though the line between the uplands and the mountains is irregular, at one point bending southward to include a spur, at another forming a deep re-entrant into the front of the range. On the Arctic slope the descent is still more abrupt. For long stretches the mountains present a bold escarpment to the north, and the sharp transition from the smooth, moss-covered (Anatuvuk) plateau to the bold, rugged mountains is very striking.

So far as is known, the Endicott Mountains embrace at least two distinct ranges. The topography is rugged and the transverse

[1] Jos. Keele, *Geol. Survey Canada, Pub. 1097*, pp. 13–18 and pl. 3.

[2] F. C. Schrader, *U.S. Geol. Survey, Prof. Paper 20.*

[3] A. H. Brooks, *op. cit.*, pp. 42–46.

valleys are sharply cut. The longitudinal valleys are broad, of gentle slopes—some of them of the basin type—and divide the group into several units. The northern or Front Range has an altitude of more than 6,000 feet, and in places peaks reach 8,000 feet. The altitude of the southern range reaches scarcely 5,000 feet. The southern range shows a remarkably even sky-line, which strongly suggests that it has been carved from a former plateau.[1]

Important topographic features that may be used in classifying all the groups herein discussed into one large major division of the North American continent are: (1) definite delimitation of each group on two sides respectively by the Great Plains and Intermontane Plateaus; (2) a high, bold "Front Range" separating the mountains from the Great Plains; (3) a range of lesser altitude and of a dissected plateau type standing behind each of the Front Ranges; and (4) a persistent *en échelon* arrangement of the Front Ranges from the Sangre de Cristo Mountains of Colorado to the Endicott Mountains of Alaska.

Within the United States the physiographic history of the Front Ranges begins with the post-Laramie deformation. This event raised the Jurassic-Cretaceous sediments into positions where they were subject to active erosion. Mature dissection of these sediments, and of the igneous bodies which had been intruded into them, of varying degrees of hardness and standing in diverse structural attitudes, has wrought the present topographic forms. The dissected plateau uplands lying west of the Front Ranges are probably remnants of a Pliocene or late Tertiary peneplain.

Schofield[2] implies a similar history for the Boundary Group, and the work of Brooks and Schrader in Alaska indicates a similar history for the Endicott Mountains. The Mackenzie group has been studied only in reconnaissance, but from what is known of its structure and stratigraphy and its relation to adjoining provinces it seems that we may be warranted in drawing the tentative deduction that it also participated in the events outlined for the United States.

[1] A. H. Brooks, *ibid.*

[2] S. J. Schofield, *Geol. Survey Canada, Guide Book No. 9*, p. 21.

[*To be continued*]

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

MILLER, WILLIAM J. *Geology of the North Creek Quadrangle, Warren County, New York.* Bull. Univ. of the State of New York. N.Y. State Museum Bull. No. 170, 1914. Pp. 90, figs. 10, pls. 14, map. 1.

Rocks described are diabase, pegmatite, gabbro, syenite, granite, and various metamorphosed rocks. Chemical analyses and recomputations into the norm are given, as well as volumetric modal analyses for many rocks which have not been chemically analyzed. Nine varieties of reaction-rims are reported. Differentiation was found in a gabbro mass. The composition varies from syenite to gabbro in the same mass, but the different phases are irregularly distributed and seem to follow no law. Contact phenomena are described, and the volumetric composition of the rock, which varies from typical gabbro to typical granite, is given for nine different zones.

The geological history of the region is told and a few pages are devoted to economic geology.

MILLER, WILLIAM J. "Magmatic Differentiation and Assimilation in the Adirondack Region," *Bull. Geol. Soc. Amer.*, XXV (1914), 243–64.

The writer describes the effects of the intrusion of great masses of syenite and granite in the Grenville rocks of the Adirondack region. He cites the older literature with regard to the differentiation in this region and shows, by his personal observations, that the inclusions of rocks of the Grenville series, varying from a few feet to a few rods in length, have been either partially or wholly fused and melted into the granite or syenite. While the author believes that stoping and engulfment of portions of the Grenville series was a common process in this region, he says that there is no positive evidence that the composition of the igneous intrusive was thereby appreciably changed.

MILLER, WILLIAM J. *Geology of the Lake Pleasant Quadrangle, Hamilton County, New York.* Bull. 182, New York State Museum, 1916. Pp. 75, pls. 10, figs. 4, map 1.

Geologic and physiographic history of the region, together with petrographic descriptions of various anorthosite-gabbros, syenites, granites, granite- and syenite-porphyries, gabbros, and diabases.

MOSES, A. J. "A Scheme for Utilizing the Polarizing Microscope in the Determination of Minerals of Non-Metallic Lustre," *School Mines Quart.*, XXXIV (1913), No. 4, pp. 30.

A very useful series of tests which may be applied to the determination of minerals as a supplement to the usual tests before the blowpipe, etc. After describing the general methods of procedure, the writer gives a 19-page key based on taste, flame-color, fusibility, and effervescence or gelatinization with acid, and final optical tests based on refractive index, interference color, optical character, and miscellaneous characteristics.

NIGGLI, PAUL. "The Phenomena of Equilibria between Silica and the Alkali Carbonates," *Jour. Amer. Chem. Soc.*, XXXV (1913), 1693–1727.

O'NEILL, J. J. *St. Hilaire (Beloeil) and Rougemont Mountains, Quebec.* Canada Dept. Mines, Mem. 43, Geol. Series 36, Ottawa, 1914. Pp. 108, map 1, bibliography.

Rising out of the plain to the east of Montreal is a series of isolated hills representing volcanic necks or laccoliths. They have been called the Monteregian Hills and may be tabulated as shown on page 188.

After giving a short account of the geology of the whole region, the author takes up the structural features of St. Hilaire and Rougemont mountains, and concludes from the evidence of undisturbed country-rock, of the coarse texture of the igneous mass close to the outer contact, of the vertical conduit through which the magma passed, of the development of flow texture in the essexite, and of the brecciation shown in the syenite at the contact, that St. Hilaire is an eroded volcanic neck. The evidence at Rougemont Mountain is not so positive. The coarse texture at the contact, which is wavy without regard to topography, and the cliff development on two sides seem to indicate that the conduit was

practically vertical. It therefore probably also represents an eroded volcanic neck.

Mountains in Order from East to West	Main Intrusion in Each in Order of Occurrence			Nature of Intrusion	Described by	Area in Sq. Miles
	No. 1	No. 2	No. 3			
Shefford.....	Essexite	Nordmarkite	Pulaskite	Laccolith	Dresser	9.0
Brome.....	Essexite to theralite	Nordmarkite to nephelite syenite, and dikes	Tinguaite	Laccolith	Dresser	30.0
Yamaska.....	Yamaskite to essexite to akerite	.....	.....	Neck	Young	5.5
Rougemont...	Yamaskite to essexite to rougemontite	.....	.....	Neck	O'Neill	9.5
Johnson.....	Essexite to pulaskite	.....	.....	Neck	Adams	0.77
St. Hilaire....	Essexite to rouvillite	Nephelite-syenite	.....	Neck	O'Neill	6.76
St. Bruno....	Essexite to syenite (umptekite)	.....	.....	Laccolith?	Dresser	2.83
Mount Royal.	Essexite	Nephelite-syenite	.....	Neck? Laccolith?	Adams Buchan	2.0

The rocks of St. Hilaire are essexite and nephelite-sodalite-syenite, with several varieties of each, and there are various dikes. Essexite was first intruded. At various places in it, brown hornblende becomes prominent. In one occurrence there is a very small amount of ferromagnesian mineral, and labradorite and nephelite greatly predominate. It is proposed to call this variety *rouvillite*. Its mode, determined by calculation based on measurements by the Rosiwal (invariably spelled Rosiwald in the report) method is, plagioclase (Ab_1An_1 to Ab_1An_4) 56 per cent, nephelite 19.5 per cent, purplish augite 7.0 per cent, hornblende 3.5 per cent, pyrite 2.5 per cent, apatite 1 per cent. The rock actually is a light-colored theralite, with a ratio of light minerals to dark of 85 to 15.

On Mount Rougemont an anorthite-olivine-gabbro occurs. It consists by volume of anorthite 52 per cent, augite 32.5 per cent, olivine 8.5 per cent, iron ore 6.5 per cent, hornblende 0.5 per cent. For this rock the name *rougemontite* is proposed.

The author suggests the probability that the Monteregian region may be part of a larger province, and the rocks may be related to the anorthosites.

Numerous analyses and recalculations into the C.I.P.W. system, as well as volumetric determinations by the Rosiwal method, are given.

Reviews

Yearbook for 1910. Illinois State Geol. Survey, Bull. No. 20, 1915. Pp. 165, pls. 14, figs. 8.

Besides the administrative report and mineral production statistics, this bulletin contains five papers of geologic interest. These reports are based on work done in co-operation with the U. S. Geological Survey.

The report of F. H. Kay on the Carlinville oil and gas field and of E. W. Shaw on the Carlyle oil field were prepared in 1911, when those fields were being developed. Both are located in south central Illinois. The rocks are monoclinal, eastward-dipping Mississippian and Pennsylvanian strata covered by glacial drift. Minor irregularities of structure determine the location of the oil pools. The Carlyle oil sands are in the upper Chester; those at Carlinville near the base of the Coal Measures. The production of both fields has decreased rapidly since 1912.

The report of E. T. Savage on the geology and mineral resources of the Springfield quadrangle appeared, in abbreviated form, as Folio 188 of the U.S. Geological Survey.

S. W. Parr contributes a paper on the valuation of coal for gas manufacture.

E. W. Shaw describes extinct Pleistocene lakes in the valleys of tributaries of the Ohio and Mississippi. The mouths of certain tributaries were dammed by aggradation by the master-streams. The deposits subsequently deposited in the ponded waters thin out upstream. The older of the lake beds are slightly younger than the Illinois till; later deposits are of Wisconsin age.

H. R. B.

Mississippi, Its Geology, Geography, Soils, and Mineral Resources. By E. N. Lowe. Miss. State Geol. Survey, Bull. No. 12, 1915. Pp. 335, pls. 28.

This volume is unique among recent state geological survey reports. The bulletin was prepared as a non-technical summary of the geology, geography, mineral resources, underground waters, and soils of the state. By the introduction of preliminary chapters treating of geologic processes, it becomes an elementary geologic textbook for the people of

Mississippi. It is admirably adapted to the needs of teachers and could well be made the basis of a practical and interesting first course in geology.

Mississippi is particularly fortunate in the publication of a report such as Mr. Lowe has prepared. It deserves a wide circulation among the people of that state.

H. R. B.

Geology and Ore Deposits of the Philipsburg Quadrangle, Montana. By. W. H. EMMONS and F. C. CALKINS. U.S. Geol. Survey, Prof. Paper 78, 1915. Pp. 271, pls. 17, figs. 55.

The Philipsburg quadrangle includes an area of 827 square miles lying immediately west and northwest of Anaconda, Montana. It is a country of strong relief, almost midway between the eastern and western divisions of the Rocky Mountains. The geologic section includes formations ranging in age from Algonkian to Recent. The Belt series, the oldest rocks in the area, is divided on lithologic grounds into six formations. Their total thickness is 15,000 feet. Next above and separated from the Belt series by a striking unconformity is the Cambrian system, comprising the Flathead, Silver Hill, Hasmark, and Red Lion formations. The Red Lion contains Upper Cambrian fossils. It is overlain by the Maywood formation, of doubtful Silurian age. The Devonian is represented only by the Jefferson limestone; the Mississippian by the Madison limestone; the Pennsylvanian by the Quadrant formation. Though the stratigraphic relations of the Paleozoic systems was not clearly made out, each is probably set off by disconformities.

The Mesozoic is not strongly developed in this part of Montana. Only three formations are here present—the Ellis, Kootenai, and Colorado. The early Tertiary was marked by powerful crustal movements. The pre-Tertiary sediments were complexly folded and overthrust and extensive igneous masses were intruded. Later the region was the scene of two epochs of vulcanism. Certain gravel deposits contain Miocene vertebrates. The Tertiary closed with tilting and a general uplift. During Pleistocene time there were at least two stages of Alpine glaciation.

The early Tertiary batholiths and smaller intrusives are granites, granodiorites, and diorites, with associated pegmatites, aplites, and lamprophyres. At and near their contacts with these intrusives the sediments are notably altered. The pneumatolytic solutions that effected these changes are believed to have carried chlorine, fluorine,

boron, iron, soda, and silica. Recrystallization cannot be relied upon as the sole explanation of the observed development of silicates and other contact minerals; they are due in part to a transfer from magmatic sources. The ores of the district are genetically related to the intrusives, their deposition representing the closing stage of igneous activity.

The first discovery of placer gold in Montana was made within the Philipsburg quadrangle in 1852. The gravels have yielded something less than $2,000,000. The total production of the underground mines, developed later, is about $50,000,000. Of this amount one-fifth is gold, the remainder silver. The deposits are of three types: fissure veins cutting both igneous and sedimentary rocks, contact metamorphic replacement deposits in limestone near the granite intrusives, and replacement deposits in sedimentary rocks.

Silver-bearing veins in granite are of principal importance, the Granite-Bimetallic mines having yielded $32,000,000. The veins follow strong, sharply defined fissures. The wall rock shows strong hydrothermal alteration of the sericite-calcite type. The primary ore has a gangue of quartz, calcite, and rhodochrosite inclosing sulphides—pyrite, stibnite, tetrahedrite, tennantite, galena, arsenopyrite, and sphalerite. Later the veins were fractured and refilled with calcite and rhodochrosite. Secondary sulphides, chiefly pyrargyrite, are conspicuously developed between the 300- and 800-foot levels. Oxidized ores containing cerargyrite, pyromorphite, and native silver occur above this zone.

At the Cable mine a contact metamorphic gold copper ore occurs in a tabular mass of limestone surrounded by granodiorite. The ore replaces limestone and consists of coarse calcite and quartz with pyrite, pyrrhotite, arsenopyrite, magnetite, and gold. The typical ore is not an intergrowth with heavy contact silicates. Those minerals formed before the principal ore deposition began.

Gold-bearing replacement veins in limestones near intrusive contacts form a transitional type. The minerals of the ore are quartz, calcite, siderite, and some pyrrhotite, magnetite, and specularite. Pyrite is the principal auriferous mineral.

This report deserves a high place among recent economic papers.

H. R. B.